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A METALLURGICAL INVESTIGATION OF LARGE FORGED DISCS OF LOW-CARBON N-155 ALLOY

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SUMMARY

This report in one of a series on a cooperative research investigation undertaken to ascertain the properties of the better wrought heat-resisting alloys in the form of large discs required for gas turbine rotors.

The properties of large discs of Low-Carbon N-155 alloy in both the as-forged and water-quenched and aged conditions have been determined by means of stress-rupture and creep tests for time periods up to about 2000 hours at 1200°, 1350°, and 1500° F. Short-time tensile test, impact test, and time-total deformation characteristics are included.

The following principal results were obtained from the 14 3/4-inch-diameter by 4 3/8-inch-thick discs:

	As-forged Disc 1L	Water quenched and Aged at 1350° F Disc 2R	Water quenched and Aged at 1500° F Disc 2L
A. Brinell hardness range			
on center plane at rim	210	200	210
on center plane at center	180	174	200
B. Offset yield strengths		(psi)	
0.2-percent offset yield strength at:			
room temperature	67,800	56,420	62,150
1200° F	46,250	31,100	39,320
1350° F	40,020	29,100	40,650
1500° F	35,600	34,500	33,850
C. Rupture-test characteristics (Stress to cause rupture in indicated time periods)		(psi)	
1200° F rupture strength			
10 hr	55,000	48,000	55,000
100 hr	46,000	41,500	44,000
1000 hr	38,500	36,000	35,000
1350° F rupture strength			
10 hr	39,000	34,500	38,000
100 hr	28,000	28,000	28,000
1000 hr	20,000	23,000	21,000
1500° F rupture strength			
10 hr	------	23,700	------
100 hr	16,500	18,500	18,000
1000 hr	11,800	13,000	12,200

The elongations and reductions of area of the fractured rupture-test specimens were quite good, and increased rupture time did not produce a significant change in ductility.

D. Total-deformation characteristics under stress

The data for the three discs tested are too voluminous to repeat in this summary. Briefly, the as-forged disc was generally superior to the heat-treated and aged discs at 1200° F. At 1350° F the superiority of the as-forged disc was lessened, and at the lower stresses disappeared. At 1500° F the heat-treated and aged discs showed increasing superiority over the as-forged disc particularly at the lower stresses which produced low rates of deformation and long life.

Aging at 1350° F, rather than at 1500° F, produced higher strengths in tests at 1350° F, and some beneficial effects from aging at 1350° F were still evident in tests at 1500° F for the test duration used in this investigation.

E. Uniformity

The properties of the discs were quite uniform considering the size of the forgings and the characteristics of the alloy.

F. Stability

The impact strength and ductility decreased after creep testing at 1200°, 1350°, and 1500° F. The strength values from tensile tests increased after creep testing at 1200° and 1350° F, and either changed very little or were slightly lowered after creep testing at 1500° F.

INTRODUCTION

This report presents the results of a study of the room-temperature, 1200°, 1350°, and 1500° F properties of three large forged discs of Low-Carbon N-155 alloy. One of the discs was tested in the as-forged condition, and the other two discs were solution treated and aged. The primary purpose of this study was to determine the level of properties exhibited by this alloy in the form of large forgings of the type required for rotor wheels in gas turbines and to determine the relative properties of as-forged and heat-treated alloy discs. The discs investigated and herein reported were several from a series now under study. The results obtained previously from similar investigations on 19-9DL, CSA, and Low-Carbon N-155 discs have been published as references 1, 2, and 3.

This work is being carried out as part of two correlated programs of research on alloys for gas-turbine applications in progress in this country. The National Advisory Committee for Aeronautics is sponsoring work directed toward the development of improved high-temperature alloys for gas turbines used in aircraft power plants. A concurrent program, formerly sponsored by the National Defense Research Committee, Office of Scientific Research and Development, and now sponsored by the Office of Naval Research, Navy Department, is being directed to the development of alloys for gas-turbine applications in general, and in particular to both ship and aircraft propulsion. The work herein was performed with the financial assistance of the National Advisory Committee for Aeronautics, the National Defense Research Committee, and the U. S. Navy.

This report is based on the joint effort of the three research programs and is being distributed by both the NACA and the Navy. The investigation of these discs for the NACA was conducted at the Department of Engineering Research of the University of Michigan, for the U. S. Navy by Battelle Memorial Institute, and for NDRC Project NRC-8 by some of the following 12 cooperating laboratories:

American Brake Shoe and Foundry Company
Battelle Memorial Institute
Crane Company
Federal Shipbuilding and Dry Dock Company
Lunkenheimer Company
Massachusetts Institute of Technology

The Midvale Company
University of Michigan
National Bureau of Standards
Research Laboratory, Westinghouse Electric
and Manufacturing Company

TEST MATERIALS

The available information concerning the discs may be summarized as follows:

Manufacturer:

Crucible Steel Company of America

Heat Number:

1X2232

Chemical Composition:

The chemical composition was reported to be the following percentages by the manufacturer:

C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	N
0.07	1.68	0.60	20.80	20.60	20.07	2.94	2.67	1.05	0.125

Fabrication Procedure:

Three 9-inch billets from a 2000-pound induction furnace heat were direct upset to produce discs 14 3/4 inches in diameter by 4 3/8 inches in thickness. The finishing temperature was about 1500° F. The left and right halves of each disc were heat treated as follows:

	Solution treatment	Aging
Disc 1L	None	Tested in the as-forged condition.
Disc 1R	None	24 hours at 1500° F
Disc 2L	2200° F, water quenched	24 hours at 1500° F
Disc 2R	2200° F, water quenched	24 hours at 1350° F
Disc 3L	2250° F, water quenched, reheated to 1500° F and reduced 3 percent, finishing temperature about 1200° F	24 hours at 1500° F

Sampling:

The code number assigned to the discs was NR-66E. Figure 1 shows the location of the samples cut from the halves of the various discs and the code system identifying the coupons. The letters refer to locations on the flat faces of the discs, and the numerals refer to the locations through the thickness of the discs.

EXPERIMENTAL PROCEDURE

The investigation was designed to provide four types of information: (1) the physical properties at room temperature, 1200°, 1350°, and 1500° F which can be expected in large forgings of the Low-Carbon N-155 analysis; (2) the effect of fabrication and heat treatment on these physical properties; (3) the variation in properties which might be present in various locations in such large forgings; and (4) the change in properties resulting from exposure to elevated temperatures under stress for prolonged time periods.

The physical-property data obtained for these large forged discs of Low-Carbon N-155 alloy included short-time tensile properties, impact strengths, rupture-test characteristics, and design curves of stress against time for total deformations of 0.1, 0.2, 0.5, and 1.0 percent at 1200°, 1350°, and 1500° F. The time-deformation data were obtained from time-deformation curves from both stress-rupture and creep tests.

The uniformity of the disc materials was checked by means of a hardness survey and by tensile and rupture tests on coupons from representative locations throughout the discs. Hardness, tensile, and impact tests and metallographic examinations on specimens after completion of the tests were used to estimate the stability of the material during prolonged exposure to temperature and stress.

The testing procedures used for the short-time tension, stress-rupture, and creep tests were in accordance with the provisions of the A.S.T.M. Recommended Practices E21-43 and E22-41.

RESULTS

The data obtained are compiled as a series of tables and figures, with the principal results from the three discs 1L, 2L, and 2R, on which most of the work was done, summarized in figures 2 to 4. The source of the data (NACA, NDRC, or Navy) is indicated in the tables.

Hardness Survey

The Brinell hardness of material cut from the discs with the five different processing and heat treatments ranged from about 165 to 235. (See fig. 5.) The hardness generally increased from the center to the rim of the disc.

The most uniform and highest over-all hardness was shown by disc 3L which was hot-cold worked after solution heat treatment. A slightly higher hardness was shown at the rim of the as-forged disc (1R) which was subsequently aged 24 hours at 1500° F after forging. The hardness of the as-forged disc which was not aged (1L) was uniformly lower than the as-forged and aged disc (1R). The hardness of the solution-treated disc aged 24 hours at 1500° F (2L) was quite uniform and was similar in magnitude to the as-forged or hot-cold worked discs (1L, 1R, and 3L). The hardness measured for disc 2R indicated that the aging for 24 hours at 1350° F as compared with 1500° F aging did not produce the maximum hardness except at the rim location where more working is accomplished in the direct-upset forging of discs from billets. It is considered that the hardness variations from center to rim of the discs were quite small, considering the size of the discs and the difficulties of forging of this highly alloyed material.

The hardness of the NR-66D disc (reference 2), which was manufactured by Universal Cyclops Steel Corporation and tested as forged and stress relieved for 2 hours at 1200° F, varied from 195 at the center to about 235 Brinell hardness at the rim of the disc on the center plane. This is very similar to the variation in hardness obtained on disc NR-66E-1R.

Short-Time Tensile Properties

The results of the short-time tensile tests at room temperature, 1200°, 1350°, and 1500° F are shown in table I. By using 1/4-inch-diameter test specimens in the room-temperature tension tests, sufficient material was available to compare the properties of the surface and interior material. The data showed slightly higher strengths for the material taken near the surface of the discs and also a slight superiority for material near the rim, as compared with the center of the discs.

In the tests at 1200° F surface test bars showed slightly higher properties than interior test bars. Comparing the three discs tested, the as-forged disc 1L showed higher strengths than the solution-treated and aged discs 2L and 2R at both room temperature and at 1200° F, but at 1350° and 1500° F superiority of the as-forged disc was shown only by the yield strengths and not by the tensile strength. The solution-treated disc aged at 1500° F was considerably stronger at room temperature and at 1200° F than the disc aged at 1350° F. The superiority produced by the 1500° F aging was considerably reduced when tested at 1350° F, and at 1500° F the two materials were quite similar in strength.

Charpy Impact Resistance

Charpy impact resistance ("V" notch) was determined on specimens from the three discs 1L, 2L, and 2R. Data are shown in table II and figures 2 to 4 from tests at room temperature, 1200°, 1350°, and 1500° F after holding at temperature for a time period sufficiently long to ensure a uniform temperature in the specimens.

The Charpy impact resistance at room temperature was lowest for the disc 2L which was water quenched and aged at 1500° F, with values of 4 to 8 foot-pounds. Aging at 1350° F, after solution treatment, as for disc 2R, produced considerably higher room-temperature impact resistance ranging from 20 to 43 foot-pounds. Similar impact resistance was shown by the as-forged disc (1L). For all three disc materials, tests at temperatures of 1200°, 1350°, and 1500° F produced considerably higher impact values than were obtained at room temperature.

Rupture-Test Characteristics

The stress-rupture data for the tests at 1200°, 1350°, and 1500° F are shown in table III, and the rupture strengths obtained from the stress-rupture time curves in figure 6 are summarized in table IV. All specimens tested were radial specimens, located as indicated in table III.

All five discs were tested at 1200° F and 100-hour and 1000-hour rupture strengths ranged from 41,500 to 47,000 psi and 34,000 to 38,500 psi respectively. The best over-all stress-rupture strength at 1200° F was shown by the as-forged disc (1L). No improvement in strength was noted for the hot-cold worked disc (3L). The strengths of the heat-treated and aged discs, 2L and 2R, were similar.

At 1350° F the 100-hour rupture strengths of the as-forged disc (1L) and the quenched and aged discs (2L and 2R) were quite similar, but at 1000 hours the heat-treated discs showed a slight superiority over the as-forged disc. The same trend existed in tests at 1500° F. At 1350° F the 100-hour rupture strengths were all 28,000 psi and the 1000-hour rupture strengths ranged from 20,000 to 23,000 psi. At 1500° F the 100-hour rupture strengths were 16,500 to 18,500 psi and the 1000-hour rupture strengths ranged from 10,400 to 11,500 psi.

Inspection of the stress-rupture time curves shown in figure 6 indicates little change in slope with increased temperature of testing for discs 2L and 2R which were solution treated and aged. The as-forged disc (1L) showed a slightly greater change in slope between 1200° and 1350° F, and the considerably steeper slope for rupture in excess of 300 hours at 1500° F clearly indicates better properties are obtained at 1500° F by the use of heat treatment.

Ductilities of the stress-rupture specimens measured after fracture were quite good. The elongation values of the as-forged disc (1L) were lower than for the heat-treated discs. Increased rupture time did not produce a significant change in ductility as is sometimes the case with other materials.

Time-Deformation Characteristics

A convenient method of describing the high-temperature strength of a material is by curves of stress against the time required for various total deformations. Data from both stress-rupture and creep tests are used to prepare such design curves. Such information along with the stress-rupture time curves gives design engineers a complete picture of the expected performance of an alloy under conditions of constant-tension stress. This information is incorporated in figures 8 to 16 for deformations of 0.1, 0.2, 0.5, and 1.0 percent at 1200°, 1350°, and 1500° F for time periods up to 3000 hours. Additional curves showing the time of transition from a minimum creep rate to the increasing rate of third-stage creep have been added so as to show when rapid elongation preceding failure starts.

The curves of stress time for total deformation were plotted from the data in tables V, VII, and IX. The data were taken from the time-deformation curves of the stress-rupture and creep tests. The time-deformation curves for the stress-rupture tests have not been included in this report but are on file at the National Advisory Committee for Aeronautics and in the Office of Naval Research, Navy Department, and may be obtained on loan for inspection if desired. The time-deformation curves for the creep tests are shown in figures 17 to 25.

Tables VI, VIII, and X show data scaled from the design curves in figures 8 to 16 and show the stresses to cause various total deformations from 0.1 to 5.0 percent in definite time periods of 1, 10, 100, 1000, and 2000 hours. For ease of comparison, similar data for the low-carbon N-155 alloy disc, NR66D, tested and reported previously in reference 2, have been included in tables VI, VIII, and X.

Creep Strengths

Many engineers are accustomed to base designs on creep rates, especially for long periods of service. For this reason, the creep-rate data have been collected from the time-deformation curves and are shown in table XI, and the logarithmic stress-creep rate curves for the tests at 1200°, 1350°, and 1500° F on the three discs 1L, 2L, and 2R are shown in figure 7. The creep rates used were either minimum rates or final rates from 1000-hour tests at 1200° F and 2000-hour tests at 1350° F and 1500° F. The creep strengths obtained from figure 7 were as follows:

Temperature (°F)	Disc	Stress for indicated creep rates (psi) 0.0001 percent/hr	0.00001 percent/hr
1200	NR-66E-1L	23,500	------
	NR-66E-2L	20,250	------
	NR-66E-2R	23,200	------
1350	NR-66E-1L	15,800	11,100
	NR-66E-2L	14,500	12,000
	NR-66E-2R	14,000	11,100
1500	NR-66E-1L	7,600	[a]4,500
	NR-66E-2L	9,500	8,000
	NR-66E-2R	10,000	7,700

[a]Estimated value.

These creep strengths can be compared with the deformation strengths in tables VI, VIII, and X. The creep strengths for a rate of 0.0001 percent per hour at 1200° F are apparently safe for use for time periods up to 10,000 hours since extrapolation of the transition point curves (stage II to stage III creep rate) in figures 8 to 10 out to 10,000 hours indicates that at the stresses listed second-stage creep would still prevail.

In the tests at 1350° and 1500° F the situation is quite different. Extrapolation of the transition curves in figures 11 to 16 shows that in most cases increasing creep rates will occur between 1000 and 2000 hours at the stress for a creep rate of 0.0001 percent per hour, and with quite large total deformations ranging from 1.0 to 2.0 percent. In the tests at 1500° F on the heat-treated and aged discs (2L and 2R), transition to third-stage creep occurs, with a total deformation of less than 0.5 percent at 10,000 psi between 1000 and 2000 hours. At the lower stresses, which produced a creep rate of 0.00001 percent per hour, longer periods of service could be attained, but the slope of the stress-rupture time curves at higher stresses strongly suggests caution should be observed when extended service periods are contemplated.

Stability Characteristics

Some of the test specimens from each of the three discs were subjected to tensile, impact, and hardness tests at room temperature after creep testing at 1200°, 1350°, and 1500° F, with the results shown in table XII. The considerable decrease in impact strength and increase in hardness were the most significant changes observed. For all three discs the highest hardness was observed after testing at 1350° F, even though, in the case of disc 2L, the specimens were aged 24 hours at 1500° F prior to creep testing.

For the as-forged disc (1L), the yield strengths were slightly higher after creep testing at 1200° and 1350° F, with no significant change in tensile strength. After creep testing at 1500° F, the room-temperature tensile and yield strengths were slightly lower than for the disc in the as-forged condition.

For the heat-treated discs (2L and 2R), the room-temperature yield strengths were materially increased by creep testing at 1200° and 1350° F. For disc 2L tested at 1200° and 1350° F and disc 2R tested at 1350° F the ductilities were reduced to very low values. Testing at 1500° F reduced the tensile and yield strengths of disc 2L, but little change was noted in the strengths of disc 2R which was heat treated and aged at 1350° F prior to creep testing.

The microstructure was quite uniform from center to rim in each of the three discs and therefore only original microstructures at a center section are shown in figure 26 at magnifications of 100X and 1000X. The grain boundaries were not developed by the etching technique used on the as-forged disc (1L), but were clearly shown in the photomicrographs of the two heat-treated and aged discs (2L and 2R). The grain-size range was from about 1 to 4 A.S.T.M. grain size. Considerable precipitation within the grains was observed in the as-forged disc.

Disc 2R, which was water quenched from 2200° F and then aged 24 hours at 1350° F, showed less precipitation within the grains than the as-forged disc. Aging at 1500° F for 24 hours (disc 2L) considerably increased the amount of precipitated phase.

The photomicrographs of figures 27, 29, and 31 show the structures of the three discs 1L, 2L, and 2R after creep testing at 1200°, 1350°, and 1500° F. Little change in structure was observed as a result of 960 hours of testing at 1200° F, but about 2000 hours of testing at 1350° or 1500° F produced a heavy general precipitation and most heavy after testing at 1350° F. Table XII indicated this precipitation was accompanied by not very large changes in room-temperature strength, but a considerable decrease in ductility and impact resistance and by increased hardness. The photomicrographs suggest that testing at 1500° F may have produced some agglomeration of the precipitated phase, since for each of the discs the room-temperature strengths were also lower after testing at 1500° F than at 1350° F.

Figures 28, 30, and 32 show the fractures and structures of specimens of the three discs after stress-rupture tests at 1200°, 1350°, and 1500° F. Fractures in the stress-rupture tests at 1200° F were largely transcrystalline, although as indicated in figure 30 there was some intergranular parting observed adjacent to the fracture in specimen 2K5. Fractures in specimens tested at 1350° F also appeared largely transcrystalline. Specimens tested in stress-rupture at 1500° F showed considerable intergranular cracking adjacent to the fracture.

DISCUSSION OF RESULTS

The tensile, rupture, and time-deformation data provide as nearly complete design information for these low-carbon N-155 discs as can be obtained in the laboratory from tests under constant-tensile stress.

The test data contained in this report apply only to the particular discs tested and fabricated and heat treated in the manner indicated. Considerable experience indicates that the properties depend on the particular manufacturing procedure used in the production of the discs. It should not be assumed that the properties herein reported apply to discs of a similar composition produced by another fabricator, or necessarily to similar discs produced by the same fabricator.

As an example of the variations that are encountered in data of the type presented, attention is called to tables VI, VIII, and X, which for purposes of comparison also include data on the as-forged disc of Low-Carbon N-155, NR-66D, (reference 2). When tested at 1200° F this previously tested as-forged disc was consistently superior to the three discs for which data are presented herein. This superiority of the as-forged NR-66D disc is maintained in tests at 1350° F except at low stresses producing creep rates of the order of 0.00001 percent per hour. In tests at 1500° F at lower stresses which produce lower rates of deformation and longer duration tests, the discs of heat-treated and aged Low-Carbon N-155 alloy are superior to the as-forged discs.

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TABLE I.- SHORT-TIME HIGH-TEMPERATURE TENSILE PROPERTIES
OF LOW-CARBON N-155 ALLOY DISCS, NR-66E.[a]

(Pulled at 0.02 in. per min to yield strength; and
0.06 in. per min to rupture.)

Disc[b]	Specimen	Specimen[c] location	Test temperature (°F)	Tensile strength (psi)	Proportional limit (psi)	Yield strengths (psi) 0.1 percent offset	Yield strengths (psi) 0.2 percent offset	Elongation (percent)	Reduction of area (percent)
NR-66E-1L	1D1	Surface C	75	115,000	34,600	59,300	65,800	32	31.8
	1E1	Surface R	75	121,000	55,000	70,000	73,700	47	61.2
	1G2A	Interior R	75	118,000	47,700	61,500	65,200	42	50.8
	1G2B	Interior R	75	118,500	44,800	63,600	66,500	47	41.6
NR-66E-2L	2F8	Surface R	75	117,000	41,700	57,500	61,200	30	23.2
	2D8	Surface C	75	108,800	50,000	62,000	65,200	16	16.1
	2D3	Interior C	75	109,400	48,100	57,800	60,700	19	18.4
	2E3	Interior R	75	111,400	48,900	58,100	61,500	15	16.9
NR-66E-2R	2K1	Surface C	75	108,000	42,800	57,100	60,600	32	30.1
	2L1	Surface C	75	106,000	39,800	54,600	58,300	34	29.5
	202A	Interior R	75	104,300	39,300	50,000	53,000	42	34.8
	2M3	Interior R	75	107,700	38,800	50,600	53,800	34	30.1
NR-66E-1L	1H1A	Surface R	1200	[d] 75,625	36,100	48,000	50,000	——	——
	1B2	Interior R	1200	79,650	34,750	40,500	42,500	22.3	25.0
NR-66E-2L	2H1A	Surface R	1200	76,500	32,200	38,500	40,400	32.6	31.2
	2B2	Interior R	1200	75,000	27,000	36,500	38,250	——	——
NR-66E-2R	2P1A	Surface R	1200	[d] 52,500	25,200	31,600	33,100	——	——
	2J2	Interior R	1200	64,700	21,000	27,650	29,100	26.0	28.8
NR-66E-1L	1B3	Interior R	1350	59,300	28,500	37,250	39,250	34.6	37.9
	1H2A	Interior R	1350	60,000	29,500	39,300	40,800	29.8	26.8
NR-66E-2L	2B3	Interior R	1350	60,700	37,500	42,500	44,000	32.0	31.8
	2H2A	Interior R	1350	59,300	26,000	35,300	37,300	31.7	32.1
NR-66E-2R	2J3	Interior R	1350	56,500	22,750	27,250	28,700	25.0	26.5
	2P2A	Interior R	1350	[d] 55,750	24,800	28,300	29,500	——	——
NR-66E-1L	1H1	Surface R	1500	45,100	20,350	28,350	35,900	33.0	40.1
	1H3A	Interior R	1500	43,700	29,400	34,300	35,300	30.8	31.8
NR-66E-2L	2H1	Surface R	1500	42,000	21,500	32,000	33,500	33.0	33.1
	2H4A	Surface R	1500	42,500	23,500	32,400	34,200	33.5	29.8
NR-66E-2R	2P1	Surface R	1500	44,300	23,250	33,750	35,300	26.7	27.5
	2P3A	Interior R	1500	42,250	24,000	32,400	33,700	31.2	34.0

[a]NDRC and Navy data.
All room-temperature tests were made on 1/4 inch-diameter specimens, gage length - 1 inch.
All high-temperature tests were made on 0.505-inch-diameter specimens, gage length - 2 inches.

[b]Heat Treatments:
NR-66E-1L As forged.
NR-66E-2L 2200° F water quenched + 24 hours at 1500° F.
NR-66E-2R 2200° F water quenched + 24 hours at 1350° F.

[c]Surface C = Surface specimen at center of disc.
Surface R = Surface specimen at rim of disc.
Interior C = Interior specimen at center of disc.
Interior R = Interior specimen at rim of disc.

[d]Specimen broke in threads at stress shown.

TABLE II.- CHARPY NOTCHED-BAR IMPACT RESISTANCE AT ROOM TEMPERATURE, 1200°, 1350°, AND 1500° F FOR LOW-CARBON N-155 ALLOY DISCS, NR-66E.[a]

Disc[b]	Specimen	Location of test specimen in disc[c]	Test temperature (°F)	Charpy impact strength (ft-lb)
NR-66E-1L	1C8 1D8	Surface C Surface R	Room	29 27
NR-66E-1L	1E6 1F6 1C6	Interior R Interior R Interior C	Room	37 46 47
NR-66E-1L	1C2 1D2 1C3	Interior C Interior C Interior C	1200	58 43 64
NR-66E-1L	1E7 1F7 1C1	Interior R Interior R Surface C	1500	45 61 60
NR-66E-2L	2C1 2D1 2C8	Surface C Surface C Surface C	Room	5 4 5
NR-66E-2L	2F3 2C6 2D6	Interior R Interior C Interior C	Room	5 7 8
NR-66E-2L	2C2 2D2 2C7	Interior C Interior C Interior C	1200	21 21 28
NR-66E-2L	2D7 2E7 2F7	Interior C Interior R Interior R	1350	29 32 32
NR-66E-2L	2E6 2F6 2C3	Interior R Interior R Interior C	1500	31 33 38
NR-66E-2R	2L8 2M8 2N8	Surface C Surface R Surface R	Room	20 38 43
NR-66E-2R	2N3 2K6 2L6	Interior R Interior C Interior C	Room	17 28 29
NR-66E-2R	2L3 2L2 2K7	Interior C Interior C Interior C	1200	61 62 60
NR-66E-2R	2L7 2M7 2N7	Interior C Interior R Interior R	1350	57 57 65
NR-66E-2R	2M6 2N6 2K3	Interior R Interior R Interior C	1500	53 56 61

[a]NDRC and Navy data.

[b]Heat Treatments:
NR-66E-1L As forged.
NR-66E-2L 2200° F water quenched + 24 hours at 1500° F.
NR-66E-2R 2200° F water quenched + 24 hours at 1350° F.

[c]Surface C = Surface specimen at center of disc.
Surface R = Surface specimen at rim of disc.
InteriorC = Interior specimen at center of disc.
InteriorR = Interior specimen at rim of disc.

TABLE III.- RUPTURE-TEST DATA FOR LOW-CARBON N-155 ALLOY DISCS, NR-66E, AT 1200°, 1350°, AND 1500° F.

Disc[a]	Specimen	Specimen location[b]	Test temperature (°F)	Stress (psi)	Rupture time (hr)	Elongation (percent)[c]	Reduction of area (percent)	Minimum creep rate (percent/hr)
[d]NR-66E-1L	1E5	CRR	1200	55,000	10	7	12.1	———
	1D5	CRC		47,500	40	10	17.8	———
	1F5	CRR		45,000	178	8	18.9	.024
	1C5	CRC		40,000	613	15	17.8	.0072
[d]NR-66E-1R	1H5	CRR	1200	50,000	51.5	35	43.7	———
	1M5	CRR		45,000	143	36	41.8	———
	1K5	CRC		40,000	237	31	24.5	———
	1L5	CRC		37,500	504	19	21.7	———
[d]NR-66E-2L	2E5	CRR	1200	50,000	26.5	15	20.0	———
	2D5	CRC		45,000	80	15	22.3	———
	2F5	CRR		40,000	205	20	24.5	.039
	2D4	CRC		35,000	1058	22	21.2	.008
[d]NR-66E-2R	2M5	CRR	1200	50,000	8	13	17.2	———
	2L5	CRC		40,000	188	10	15.6	———
	2K5	CRC		35,000	1536	12	18.9	.0026
[d]NR-66E-3L	3D5	CRC	1200	48,000	61	23	23.9	———
	3E5	CRR		45,000	139	20	27.7	———
	3C5	CRC		40,000	228	18	24.5	———
[d]NR-66E-1L	1C4-1	CRC	1350	30,000	60	35	30.8	———
	1C4-2	CRC		25,000	239	34	36.9	.055
	1D4	CRC		21,500	624	25	45.6	.013
[d]NR-66E-2L	[f]2C5	CRC	1350	30,000	52	26	35.0	———
	[f]2C4-1	CRC		25,000	258	36	39.8	.059
	2C4-2	CRC		21,500	729	35	39.8	.013
[e]NR-66E-2L	2H3	CRR	1350	25,000	133	52	57.0	.15
	2H2	CRR		22,000	431	46	51.0	.037
	2H4	CRR		17,500	Discontinued after 5 percent deformation.			.0014
[d]NR-66E-2R	2P4	CRR	1350	32,500	46	33	36.6	———
	2K4-1	CRC		30,000	96	24	30.8	———
	2L4-1	CRC		27,500	60	9	14.4	———
	2P5	CRR		27,500	276	23	31.5	———
	2K4-2	CRC		25,000	392	30	37.2	.029
	2L4-2	CRC		23,000	1068	34	39.8	.0032
[e]NR-66E-1L	1D3	CRC	1500	18,000	40.5	39.0	36.6	———
	1H2	CRR		17,000	113.3	15.1	30.8	.044
	1E3	CRR		16,000	306.0	12.0	16.0	.012
	1E4	CRR		14,000	449.0	7.0	12.5	.005
	1F3	CRR		13,000	556.0	12.0	11.6	.004
	1F4	CRR		10,500	1084.0	4.0	8.8	.002
[e]NR-66E-2L	2E1	SRR	1500	20,000	53	41	43.0	———
	2E2	CRR		18,000	60	61	52.1	———
	2F1	SRR		17,000	186	46	64.5	.044
	2G2	CRR		17,000	Discontinued after 2 percent deformation.			.092
	2F2	CRR		15,000	323	41	58.1	.024
	2E4	CRR		13,000	579	44	54.8	.01
	2F4	CRR		11,000	1885	37	43.4	.0013
[e]NR-66E-2R	2M1	SRR	1500	22,500	16	42	39.5	———
	2N2	CRR		20,000	32	34	42.9	———
	2N1	SRR		17,000	180	40	52.8	———
	2M2	CRR		15,000	485	42	54.2	.008
	2P3	CRR		15,000	Discontinued after 2 percent deformation			.022
	2P4	SRR		13,500	Discontinued after 1 percent deformation			.0034
	2N4	CRR		13,500	940	37	53.3	.004
	2J1	SRR		10,000	3062	21	33.0	.0001

[a]Heat Treatments:
NR-66E-1L: As forged.
NR-66E-1R: As forged + 24 hours at 1500° F.
NR-66E-2L: 2200° F water quenched + 24 hours at 1500° F.
NR-66E-2R: 2200° F water quenched + 24 hours at 1350° F.
NR-66E-3L: 2250° F water quenched + 3 percent hot-cold work at 1500° to 1200° F + 24 hours at 1500° F.

[b]CRR Radial specimen from center plane at rim of disc.
CRC Radial specimen from center plane at center of disc.
SRR Radial specimen from surface plane at rim of disc.

[c]Percent in 1 inch.

[d]NACA data (specimens were 0.160 in. in diameter with a gage length of 1 in.)

[e]WDRC and Navy data (specimens were 0.250 in. in diameter with a gage length of 1.3 in.).

[f]Data from this test not used in design curves.

TABLE IV.- RUPTURE STRENGTHS OF LOW-CARBON N-155 ALLOY DISCS, NR-66E, AT 1200°, 1350°, AND 1500° F.

Disc[a]	Test temperature (°F)	Stress to produce rupture in indicated time periods (psi)			
		10 hr	100 hr	1000 hr	2000 hr
[b]NR-66E-1L	1200	55,000	46,000	38,500	[d]36,500
[b]NR-66E-1R	1200	------	47,000	33,500	[d]30,000
[b]NR-66E-2L	1200	[d]55,000	44,000	35,000	[d]33,000
[b]NR-66E-2R	1200	48,000	41,500	36,000	34,500
[b]NR-66E-3L	1200	------	46,000	[d]34,000	------
[b]NR-66E-1L	1350	[d]39,000	28,000	20,000	[d]18,000
[b]NR-66E-2L	1350	[d]38,000	28,000	21,000	[d]19,000
[b]NR-66E-2R	1350	[d]34,500	28,000	23,000	22,000
[c]NR-66E-1L	1500	------	16,500	11,800	10,400
[c]NR-66E-2L	1500	------	18,000	12,200	10,700
[c]NR-66E-2R	1500	23,700	18,500	13,000	11,500

[a]Heat Treatments:

NR-66E-1L As forged.
NR-66E-1R As forged + 24 hours at 1500° F.
NR-66E-2L 2200° F water quenched + 24 hours at 1500° F.
NR-66E-2R 2200° F water quenched + 24 hours at 1350° F.
NR-66E-3L 2250° F water quenched + 3 percent hot-cold work at 1500° to 1200° F + 24 hours at 1500° F.

[b]NACA data.

[c]NDRC and Navy data.

[d]Estimated.

TABLE V.- STRESS-TIME FOR TOTAL-DEFORMATION DATA AT 1200° F FOR LOW-CARBON N-155 ALLOY DISCS, NR-66E.[a]

Disc[b]	Specimen	Stress (psi)	Initial deformation (percent)	Time for indicated total deformation (hr)						Transition to third-stage creep	
				0.1%	0.2%	0.5%	1.0%	2.0%	5.0%	Time (hr)	Deformation (percent)
NR-66E-1L	1A2	25,000	0.114	—	87	1150	—	—	—	—	—
	1A3	30,000	.131	—	21	145	617	—	—	—	—
	1C5	40,000	.22	—	—	2	11	46	325	335	5.3
	1F5	45,000	.55	—	—	—	5	30	150	150	5.0
NR-66E-2L	2A3	20,000	.080	60	1290	—	—	—	—	—	—
	2A2	25,000	.111	—	85	625	—	—	—	—	—
	2D4	35,000	.18	—	—	22	57	165	515	475	4.5
	2F5	40,000	.40	—	—	—	6	24	96	90	4.7
NR-66E-2R	2I2	25,000	.139	—	245	—	—	—	—	—	—
	2I3	30,000	.61	—	—	—	335	—	—	—	—
	2K5	35,000	[c]1.00	—	—	—	—	47	885	975	5.2

[a]NACA data.

[b]Heat Treatments:
NR-66E-1L As forged.
NR-66E-2L 2200° F water quenched + 24 hours at 1500° F.
NR-66E-2R 2200° F water quenched + 24 hours at 1350° F.

[c]Approximate.

TABLE VI.- STRESS-TIME FOR TOTAL-DEFORMATION CHARACTERISTICS AND CREEP STRENGTHS AT 1200° F FOR LOW-CARBON N-155 ALLOY DISCS, NR-66E[a].

Disc[b]	Total deformation (percent)	Stress to cause total deformation in indicated time periods (psi)					Creep strength (Based on creep rates at 1000 hr) (psi)	
		1 hr	10 hr	100 hr	1000 hr	2000 hr	0.00010% per hr	0.00001% per hr
NR-66D	0.1	21,500	20,000	17,500	14,500	13,500	28,000	15,000
NR-66E-1L	.1	------	------	------	------	------	23,500	------
NR-66E-2L	.1	------	------	19,500	------	------	20,250	------
NR-66E-2R	.1	------	------	------	------	------	23,200	------
NR-66D	.2	34,000	31,500	28,000	24,000	23,000		
NR-66E-1L	.2	------	31,000	25,000	------	------		
NR-66E-2L	.2	------	------	24,500	20,500	19,000		
NR-66E-2R	.2	------	------	[c]26,000	[c]23,000	------		
NR-66D	.5	44,500	39,500	35,000	30,000	28,500		
NR-66E-1L	.5	41,500	36,000	30,500	25,500	23,500		
NR-66E-2L	.5	------	------	30,000	23,500	------		
NR-66E-2R	.5	------	------	------	------	------		
NR-66D	1.0	51,000	45,500	40,000	35,000	33,500		
NR-66E-1L	1.0	------	40,500	34,500	28,500	------		
NR-66E-2L	1.0	------	40,000	33,000	------	------		
NR-66E-2R	1.0	------	------	[c]31,000	29,000	------		
NR-66D	Transition	------	------	51,500	39,500	36,000		
NR-66E-1L	Transition	------	------	44,500	37,000	------		
NR-66E-2L	Transition	------	------	40,500	32,000	------		
NR-66E-2R	Transition	------	------	------	35,000	------		

[a]NACA data.

[b]Heat Treatments:

- NR-66D: As forged + 2 hours at 1200° F.
- NR-66E-1L: As forged.
- NR-66E-2L: 2200° F water quenched + 24 hours at 1500° F.
- NR-66E-2R: 2200° F water quenched + 24 hours at 1350° F.

[c]Estimated values.

TABLE VII.- STRESS-TIME FOR TOTAL DEFORMATION DATA AT 1350° F FOR LOW-CARBON N-155 ALLOY DISCS, NR-66E.

Disc[a]	Specimen	Stress (psi)	Initial deformation (percent)	Time for indicated total deformation (hr)						Transition to third-stage creep	
				0.1%	0.2%	0.5%	1%	2%	5%	Time (hr)	Deformation (percent)
NR-66E-1L	(b) 1G4	10,000	0.053	65	360	—	—	—	—	—	—
	(b) 1B4	12,000	.062	37	160	[g]4900	—	—	—	—	—
	(b) 1A4	15,000	.072	14	85	447	—	—	—	—	—
	(b) 1G1	20,000	.15	—	2	32	120	—	—	—	—
	(c) 1D4	21,500	.10	—	—	6	22	60	200	310	6.4
	(c) 1C4-2	25,000	.12	—	—	1	5	20	75	130	8.0
NR-66E-2L	(b) 2G3	10,000	.045	127	450	—	—	—	—	—	—
	(b) 2B4	12,000	.052	58	200	—	—	—	—	—	—
	(b) 2A4	15,000	.083	20	125	625	—	—	—	—	—
	(b) 2H4	17,500	.115	—	5	36	114	622	—	715	2.15
	(b) 2G4	20,000	.175	—	1	11	36.5	119	—	—	—
	(b) 2H2	22,000	.122	—	—	4	16	37	112	150	6.5
	(b) 2H3	25,000	.153	—	—	1	4	11	60	45	3.6
	(c) [d]2G4-2	21,500	.105	—	—	15	36	70	235	290	5.6
	(c) 2G4-1	25,000	.135	—	—	3	9	26	68	120	8.2
NR-66E-2R	(b) 2O3	10,000	[e].04	230	540	—	—	—	—	—	—
	(b) 2J4	12,000	[e].072	40	175	—	—	—	—	—	—
	(b) 2I4	15,000	[e].085	10	90	480	—	—	—	—	—
	(b) 2O4	20,000	[f].10	—	13	90	[g]220	—	—	—	—
	(c) 2L4-2	23,000	.13	—	—	12	48	112	600	550	4.5
	(c) 2K4-2	25,000	.14	—	—	4	14	44	112	250	9.0
	(c) 2P5	27,500	.18	—	—	3	8	28	79	160	8.8
	(c) 2K4-1	30,000	.19	—	—	—	3	10	28	—	—
	(c) 2P4	32,500	.21	—	—	—	1	5	16	—	—

[a]Heat Treatments:
NR-66E-1L: As forged.
NR-66E-2L: 2200° F water quenched + 24 hours at 1500° F.
NR-66E-2R: 2200° F water quenched + 24 hours at 1350° F.

[b]NDRC and Navy data.

[c]NACA data.

[d]Data from this test not used in design curves.

[e]Initial deformation obtained from load-off reading.

[f]Initial deformation calculated from modulus of elasticity.

[g]Estimated.

TABLE VIII.- STRESS-TIME FOR TOTAL DEFORMATION CHARACTERISTICS AND CREEP STRENGTHS AT 1350° F FOR LOW-CARBON N-155 ALLOY DISCS, NR-66E[a].

Disc[b]	Total deformation (percent)	Stress to cause total deformation in indicated time periods (psi)					Creep strength (Based on creep rates at 1000 hr) (psi)	
		1 hr	10 hr	100 hr	1000 hr	2000 hr	0.0001% per hr	0.00001% per hr
NR-66D	0.1	17,000	13,800	11,000	8,000	—	16,000	7,900
NR-66E-1L	.1	[c]18,600	15,500	—	—	—	15,800	11,100
NR-66E-2L	.1	[c]18,300	15,700	10,600	—	—	14,500	12,000
NR-66E-2R	.1	—	15,000	10,900	—	—	14,000	11,100
NR-66D	.2	26,000	21,400	16,700	12,000	[c]10,700		
NR-66E-1L	.2	[c]20,800	17,800	14,200	—	—		
NR-66E-2L	.2	20,000	17,200	13,700	—	—		
NR-66E-2R	.2	—	20,400	14,400	—	—		
NR-66D	.5	—	26,500	22,000	17,200	[c]15,900		
NR-66E-1L	.5	24,500	21,400	17,800	[c]13,900	—		
NR-66E-2L	.5	25,000	20,200	16,400	[c]14,000	—		
NR-66E-2R	.5	—	24,000	19,700	[c]14,100	[c]13,200		
NR-66D	1.0	—	—	25,000	19,500	—		
NR-66E-1L	1.0	—	23,200	20,200	—	—		
NR-66E-2L	1.0	—	22,900	17,800	—	—		
NR-66E-2R	1.0	—	26,900	21,600	—	—		
NR-66D	Transition	—	—	24,000	18,000	—		
NR-66E-1L	Transition	—	—	26,000	—	—		
NR-66E-2L	Transition	—	—	23,000	17,000	—		
NR-66E-2R	Transition	—	—	[c]27,800	—	—		

[a]NACA, NDRC and Navy data.

[b]Heat Treatments:

NR-66D: As forged + 2 hours at 1200° F.
NR-66E-1L: As forged.
NR-66E-2L: 2200° F water quenched + 24 hours at 1500° F.
NR-66E-2R: 2200° F water quenched + 24 hours at 1350° F.

[c]Estimated values.

TABLE IX.- STRESS-TIME FOR TOTAL DEFORMATION DATA AT 1500° F FOR LOW-CARBON N-155 ALLOY DISCS, NR-66E[a].

Disc[b]	Specimen	Stress (psi)	Initial deformation (percent)	Time for indicated total deformation (hr)						Transition to third-stage creep	
				0.1%	0.2%	0.5%	1%	2%	5%	Time (hr)	Deformation (percent)
NR-66E-1L	1G3	5,000	0.031	65	[d]4800	—	—	—	—	—	—
	1A1	7,000	.042	37	400	[d]9000	—	—	—	—	—
	1B1	10,000	.065	9	47	615	1963	—	—	1400	0.8
	1F4	10,500	—	8	26	108	360	740	—	550	1.40
	1F3	13,000	—	4	8	40	97	320	596	360	2.15
	1E4	14,000	—	—	—	38	96	290	430	250	1.72
	1E3	16,000	—	—	—	20	64	138	290	160	2.30
	1H2	17,000	.093	—	—	5	16	37	—	25	1.30
NR-66E-2L	2H2	5,000	.038	750	—	—	—	—	—	—	—
	2A1	7,000	.037	210	[d]8700	—	—	—	—	—	—
	2B1	10,000	.059	9	52	1620	2035	—	—	1200	0.375
	2F4	11,000	—	—	25	125	475	785	1135	600	1.40
	2E4	13,000	—	—	—	48	88	186	315	145	1.50
	2F2	15,000	—	—	—	5	16	65	160	50	1.70
	[c]2F1	17,000	—	—	—	11	23	45	90	28	1.20
	2G2	17,000	.115	—	—	3.1	8.7	17	—	10	1.10
NR-66E-2R	2P2	5,000	.025	—	—	—	—	—	—	—	—
	2I1	7,000	.046	425	[d]18,000	—	—	—	—	—	—
	2J1	10,000	.066	10	45	1240	1615	1775	2255	800	0.38
	2P4	13,500	.078	0.2	7	55	174	—	—	120	0.75
	[c]2M2	13,500	—	—	—	—	—	190	580	—	—
	2P3	15,000	.082	—	2.7	15.4	37.5	74	—	50	1.3

[a]NDRC and Navy data.

[b]Heat Treatments:
NR-66E-1L: As forged.
NR-66E-2L: 2200° F water quenched + 24 hours at 1500° F.
NR-66E-2R: 2200° F water quenched + 24 hours at 1350° F.

[c]Data from this test not used in design curves.

[d]Estimated.

TABLE X.- STRESS-TIME FOR TOTAL DEFORMATION CHARACTERISTICS AND CREEP STRENGTHS AT 1500° F FOR LOW-CARBON N-155 ALLOY DISCS, NR-66E[a].

Disc[b]	Total deformation (percent)	Stress to cause total deformation in indicated time periods (psi)					Creep strength (Based on minimum creep rates) (psi)	
		1 hr	10 hr	100 hr	1000 hr	2000 hr	0.00010% per hr	0.00001% per hr
NR-66D	0.1	16,000	11,500	7,700	[c]5,300	———	8,700	[c]5,000
NR-66E-1L	.1	———	9,800	4,800	———	———	7,600	[c]4,500
NR-66E-2L	.1	[c]13,500	10,500	7,500	4,800	———	9,500	8,000
NR-66E-2R	.1	11,800	10,000	8,200	6,800	[c]6,600	10,000	7,700
NR-66D	.2	———	16,800	11,000	6,800	———		
NR-66E-1L	.2	16,000	12,500	8,800	[c]6,200	[c]5,700		
NR-66E-2L	.2	15,200	12,200	9,600	[c]8,300	[c]7,800		
NR-66E-2R	.2	———	12,700	9,600	8,400	[c]8,000		
NR-66D	.5	———	———	15,500	10,500	[c]9,300		
NR-66E-1L	.5	———	16,500	11,000	9,200	[c]8,600		
NR-66E-2L	.5	———	14,600	11,300	10,200	———		
NR-66E-2R	.5	———	15,400	12,800	10,200	[c]9,300		
NR-66D	1.0	———	———	17,400	12,000	———		
NR-66E-1L	1.0	———	———	13,400	10,200	10,000		
NR-66E-2L	1.0	———	16,200	12,800	10,500	10,000		
NR-66E-2R	1.0	———	[c]16,300	14,000	10,800	9,700		
NR-66D	Transition	———	———	16,400	11,200	9,700		
NR-66E-1L	Transition	———	———	16,300	10,200	[c]9,800		
NR-66E-2L	Transition	———	17,000	13,700	10,300	———		
NR-66E-2R	Transition	———	[c]17,800	13,800	9,600	———		

[a]NDRC and Navy data.

[b]Heat Treatments:
- NR-66D: As forged + 2 hours at 1200° F.
- NR-66E-1L: As forged.
- NR-66E-2L: 2200° F water quenched + 24 hours at 1500° F.
- NR-66D-2R: 2200° F water quenched + 24 hours at 1350° F.

[c]Estimated values.

TABLE XI.- CREEP TEST DATA AT 1200°, 1350°, AND 1500° F FOR LOW-CARBON N-155 ALLOY DISCS, HR-66B

Disc[a]	Specimen	Test temperature (°F)	Stress (psi)	Duration (hr)	Deformation upon application of load (percent)	Creep rate, percent per hour at 500 hr	Creep rate, percent per hour at 1000 hr	Creep rate, percent per hour at 1500 hr	Creep rate, percent per hour at 2000 hr	Total deformation, percent at 500 hr	Total deformation, percent at 1000 hr	Total deformation, percent at 1500 hr	Total deformation, percent at 2000 hr
HR-66B-1L	(b) 1A3	1200	30,000	940	0.131	0.00078	0.00051	———	———	0.915	1.210	———	———
	1A2	1200	25,000	1078	.114	.00027	.00016	———	———	.373	.475	———	———
HR-66B-2L	(b) 2A2	1200	25,000	1078	.111	.00049	.00049	———	———	.438	.684	———	———
	2A3	1200	20,000	1292	.060	.000077	.000077	———	———	.140	.177	———	———
HR-66B-2R	(b) 2B3	1200	30,000	940	.61	.00098	.00078	———	———	1.16	1.56	———	———
	2B2	1200	25,000	1077	.139	.00018	.00018	———	———	.246	.336	———	———
HR-66B-1L	(c) 1B1	1350	20,000	267	.15	[d].0039	———	———	———	[d]1.35	———	———	———
	1A4	1350	15,000	2016	.073	.000358	.000150	0.000079	0.000054	.521	.614	0.666	0.700
	1B4	1350	12,000	2015	.062	.000180	.000084	.000039	.000020	.384	.416	.432	.442
	1C4	1350	10,000	2086	[e].053	.000175	.000038	.000064	Nil	.326	.304	.334	.340
HR-66B-2L	(c) 2B4	1350	20,000	240	.175	[f].004	———	———	———	[f]2.99	———	———	———
	2A4	1350	15,000	2012	[e].083	.000336	.000098	.000055	.000025	.469	.531	.566	.585
	2B4	1350	12,000	2016	.052	.000166	.000047	.000033	.000019	.322	.348	.378	.390
	2C3	1350	10,000	2012	.045	.00012	.000019	.000017	.000018	.222	.243	.257	.266
HR-66B-2R	(c) 204	1350	20,000	214	[g].10	[h].0038	———	———	———	[h].976	———	———	———
	214	1350	15,000	1990	[e].085	.000302	.000097	.000041	.000039	.513	.556	.583	.603
	2A4	1350	12,000	2015	[e].072	.000188	.000042	.000032	.000033	.338	.390	.412	.426
	203	1350	10,000	2008	[g].040	.000124	.000045	.000055	.000014	.196	.234	.246	.259
HR-66B-1L	(c) 1B1	1500	10,000	2033	.065	.00033	.00033	.00038	.00053	.497	.627	.812	1.05
	1A1	1500	7,000	2037	.048	.000085	.000054	.000039	.000040	.212	.240	.268	.290
	1B3	1500	5,000	2010	.031	.000030	.000038	.000042	.000013	.150	.161	.170	.172
HR-66B-2L	(c) 2B1	1500	10,000	2611	.059	.00011	.00013	.00030	.00198	.307	.357	.466	.940
	2A1	1500	7,000	2775	[g].037	.000036	.000022	.000010	.000010	.119	.135	.143	.147
	2B2	1500	5,000	2252	.038	.000080	.000010	.000006	Nil	.096	.104	.130	.110
HR-66B-2R	(c) 2B1	1500	10,000	[i]3067	.064	.00010	.00024	.00150	.00475	.330	.425	.760	2.74
	2A1	1500	7,000	2204	.046	.000060	.000010	.000005	.000004	.106	.130	.132	.136
	2B2	1500	5,000	1485	.085	.000080	Nil	Nil	———	.065	.070	.070	

[a]Heat treatments:
HR-66B-1L: As forged.
HR-66B-2L: 2200° F water quenched + 24 hours at 1500° F.
HR-66B-2R: 2200° F water quenched + 24 hours at 1350° F.

[b]NACA data.

[c]NDRC and Navy data.

[d]When discontinued at 267 hours.

[e]Value obtained from contraction when load was removed.

[f]When discontinued at 240 hours.

[g]Value obtained using the Modulus of Elasticity.

[h]When discontinued at 214 hours.

[i]Broke, 21.4% elongation, 33.0% reduction of area.

TABLE XII.- EFFECT OF CREEP TESTING ON THE ROOM-TEMPERATURE PHYSICAL PROPERTIES OF LOW-CARBON N-155 ALLOY DISCS, NR-66E.

Disc[a]	Specimen	Prior testing conditions: Temp. (°F)	Stress (psi)	Time (hr)	Residual room-temperature properties: Tensile strength (psi)	Offset yield strength (psi): 0.02%	0.1%	0.2%	Proportional limit (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Izod impact strength (ft-lb)	Vickers hardness
NR-66E-1L	(b) 62A	Original condition			118,000	—	61,500	65,200	47,700	42	50.8	—	—
	(b) 62B	do.			118,500	—	63,600	66,500	44,800	47	41.6	—	—
	[c]1H4-A	do.			—	—	—	—	—	—	—	[d]60, 60	215
	(b) 1H4-B	do.			—	—	—	—	—	—	—	[e]71, 41	—
	(b) 1G2	do.			—	—	—	—	—	—	—	[e]63, 53	—
	(c) 1A2	1200	25,000	1070	116,000	62,500	69,400	71,500	50,000	22	22.7	—	—
	(c) 1A3	1200	30,000	960	—	—	—	—	—	—	—	[d]11, 12	249
	(b) 1G4	1350	10,000	2086	124,400	—	67,000	71,800	44,400	[f]7.5	—	—	—
	(b) 1B4	1350	12,000	2015	—	—	—	—	—	—	—	[e]2.5, 2	293
	(b) 1G3	1500	5,000	1745	114,700	—	57,500	61,700	40,800	11	12.3	—	—
	(b) 1A1	1500	7,000	2037	—	—	—	—	—	—	—	[e]10, 5.5	233
NR-66E-2L	(b) 2D3	Original condition			109,400	—	57,800	60,700	48,100	19	18.4	—	—
	(b) 2E3	do.			111,400	—	58,100	61,500	48,900	15	16.9	—	—
	[c]2H4	do.			—	—	—	—	—	—	—	[d]6, 6	240
	(b) 2H3	do.			—	—	—	—	—	—	—	[e]10, 6	—
	(b) 2G1	do.			—	—	—	—	—	—	—	[e]7, 7	—
	(c) 2A3	1200	20,000	1292	101,500	60,000	65,500	68,500	37,500	[g]5	5.4	—	—
	(c) 2A2	1200	25,000	1070	—	—	—	—	—	—	—	[d]2, 3	247
	(b) 2G3	1350	10,000	2012	103,200	—	65,400	69,500	44,700	2.5	3.1	—	—
	(b) 2B4	1350	12,000	2016	—	—	—	—	—	—	—	[e]1.5, 1.5	280
	(b) 2H2	1500	5,000	2252	93,400	—	50,700	54,500	29,200	3.5	4.6	—	—
	(b) 2A1	1500	7,000	2775	—	—	—	—	—	—	—	[e]2.5, 2	237
NR-66E-2R	(b) 202-A	Original condition			104,300	—	50,000	53,000	39,300	42	34.8	—	—
	(b) 2H3	do.			107,700	—	50,600	53,800	38,800	34	30.1	—	—
	[c]201	do.			—	—	—	—	—	—	—	[d]22, 26	205
	(b) 202-B	do.			—	—	—	—	—	—	—	[e]30, 40	—
	(b) 2F4	do.			—	—	—	—	—	—	—	[e]26, 31	—
	(c) 2I2	1200	25,000	1070	102,000	51,500	57,000	60,000	37,500	24	19.2	—	—
	(c) 2I3	1200	30,000	960	—	—	—	—	—	—	—	[d]4, 10	224
	(b) 203	1350	10,000	2008	113,300	—	69,000	73,800	44,900	3.0	4.3	—	—
	(b) 2J4	1350	12,000	2015	—	—	—	—	—	—	—	[e]5, 3.5	276
	(b) 2P2	1500	5,000	1485	101,800	—	50,000	54,100	27,000	4.0	6.2	—	—
	(b) 2I1	1500	7,000	2204	—	—	—	—	—	—	—	[e]3, 3.5	238

[a]Heat Treatments:
NR-66E-1L: As forged.
NR-66E-2L: 2200° F water quenched + 24 hours at 1500° F.
NR-66E-2R: 2200° F water quenched + 24 hours at 1350° F.

[b]NDRC and Navy data.

[c]NACA data.

[d]Specimens were 0.365-inch square with a 0.050-inch V-notch.

[e]Specimens were 0.450-inch diameter, V-notch.

[f]Broke in fillet.

[g]Specimen fractured in gage mark.

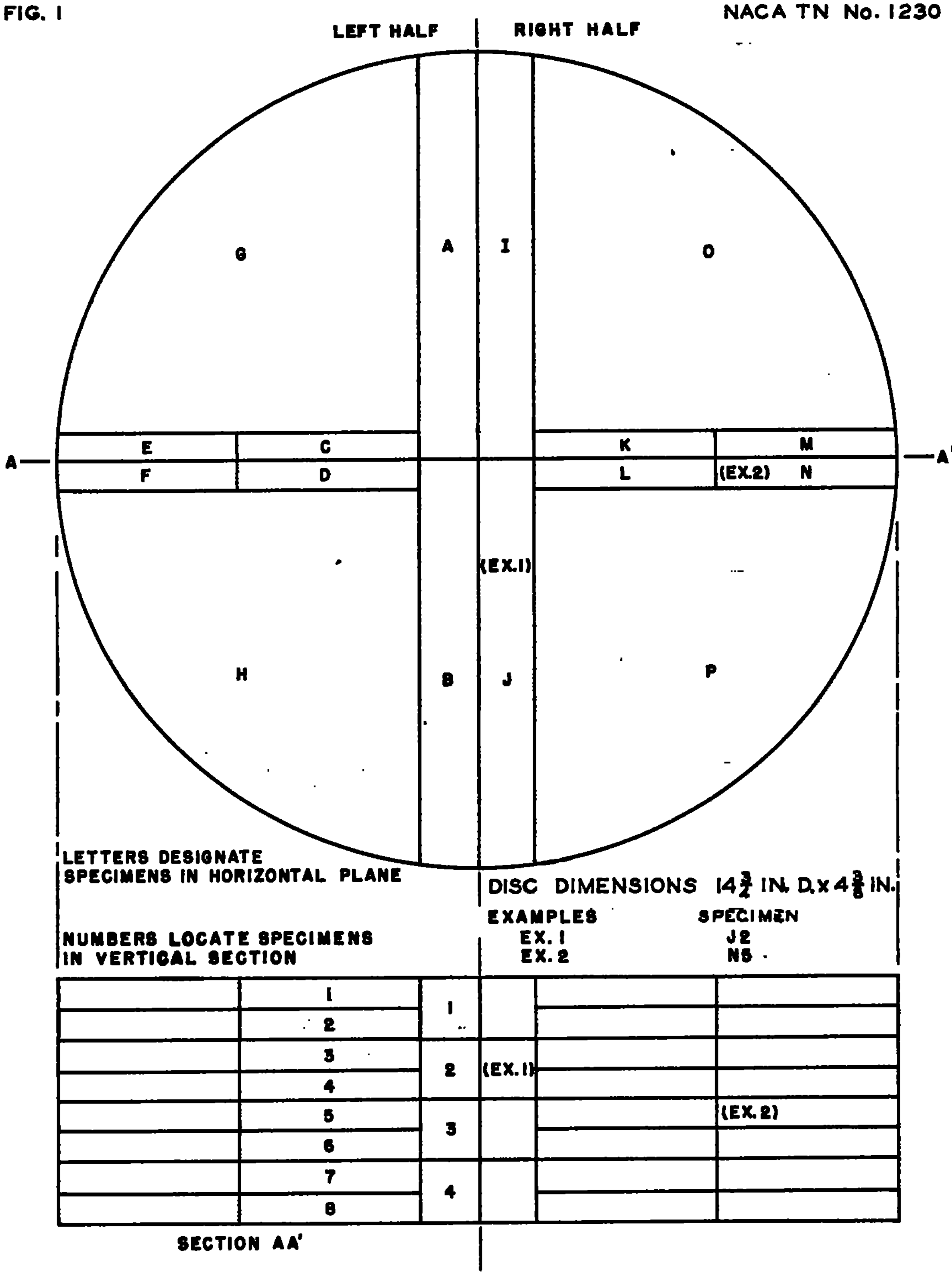


FIGURE 1.—LOCATION OF TEST COUPONS IN LOW-CARBON N-155 ALLOY DISCS, NR-66E.

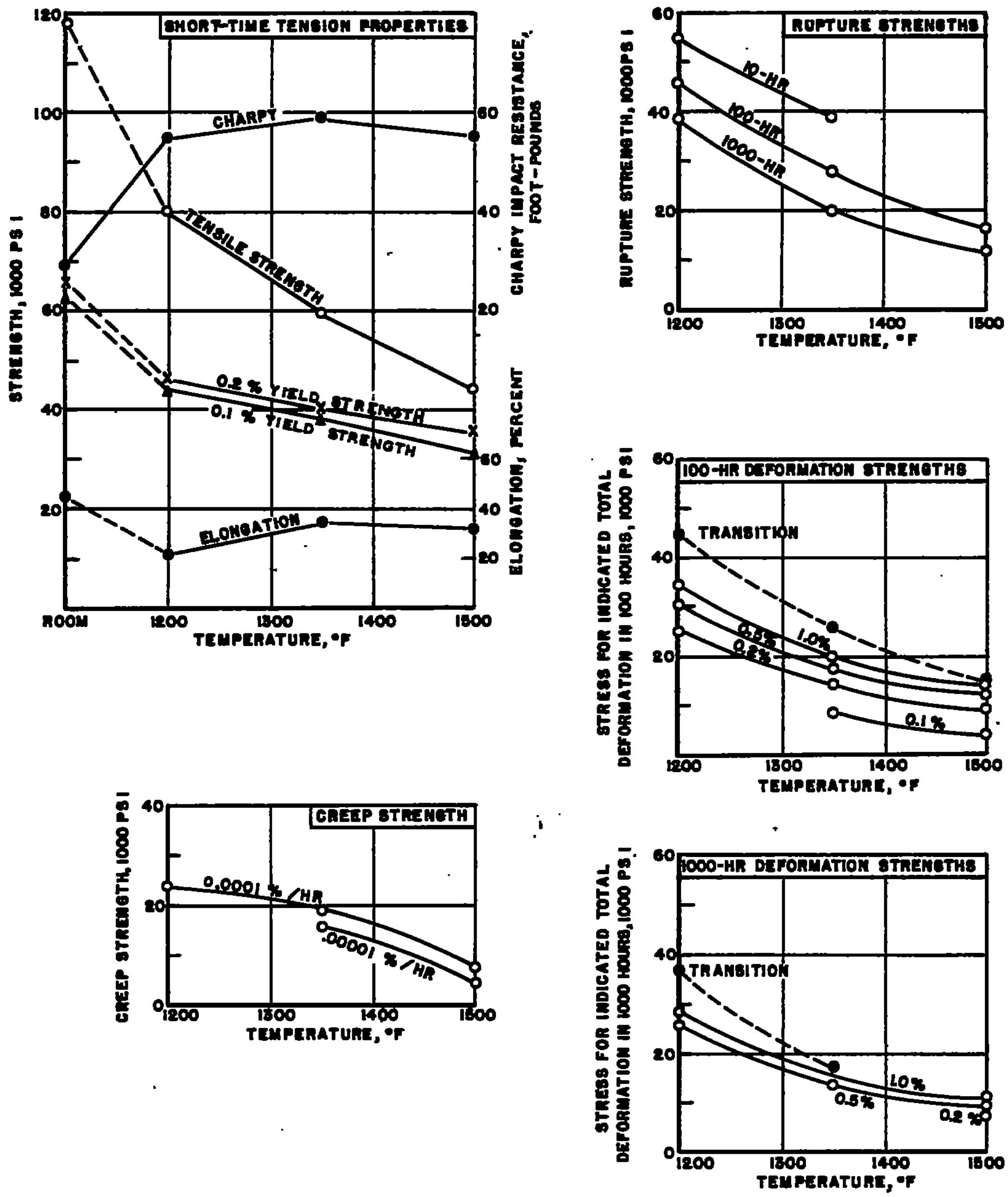


FIGURE 2.-SUMMARY OF THE PROPERTIES OF THE LOW-CARBON N-155 ALLOY DISC, NR-66E-IL. (TESTED AS FORGED)

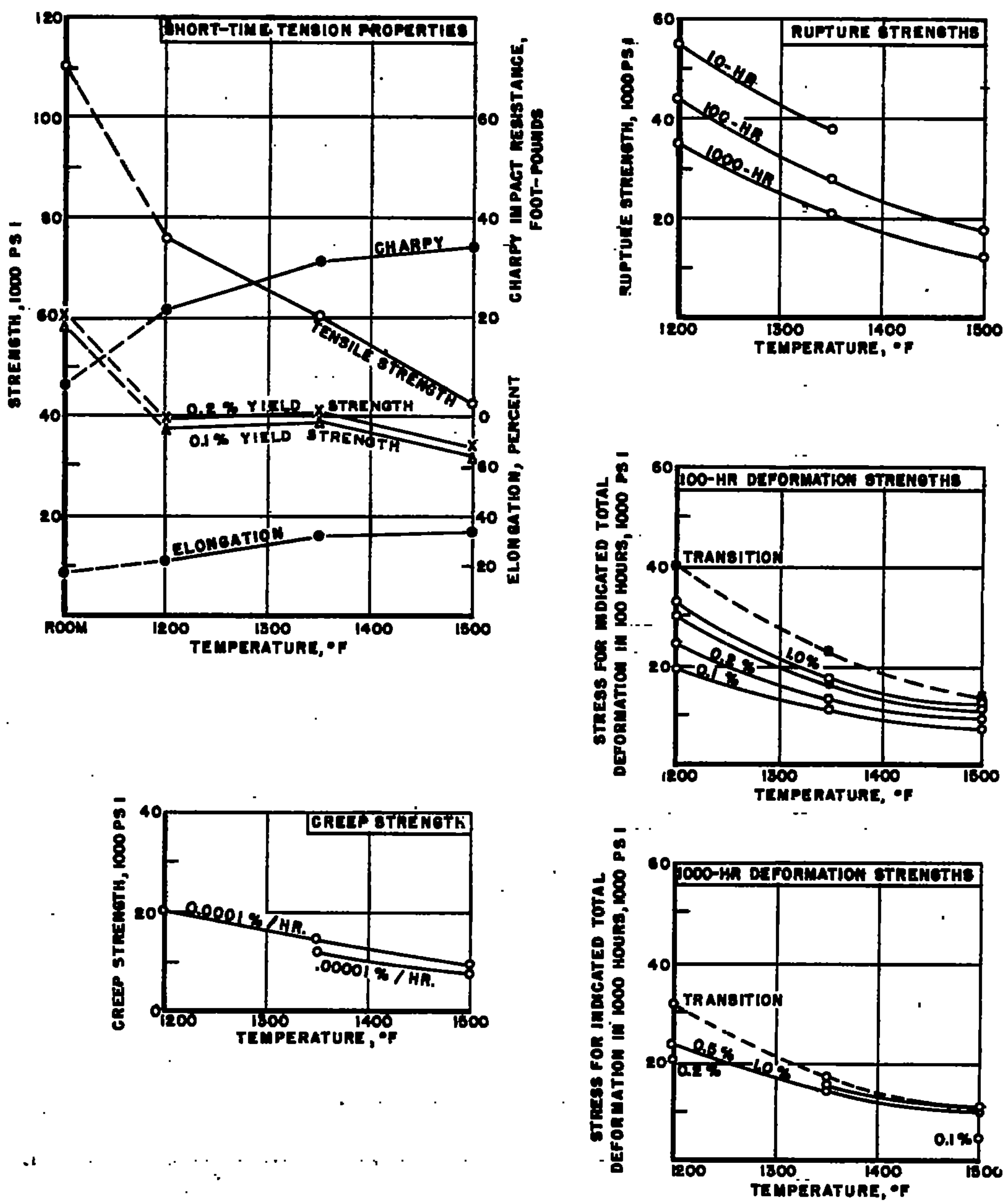


FIGURE 3.—SUMMARY OF THE PROPERTIES OF THE LOW-CARBON N-155 ALLOY DISC, NR-66E-2L. (TESTED AS WATER-QUENCHED FROM 2200 °F AND AGED 24 HOURS AT 1500 °F)

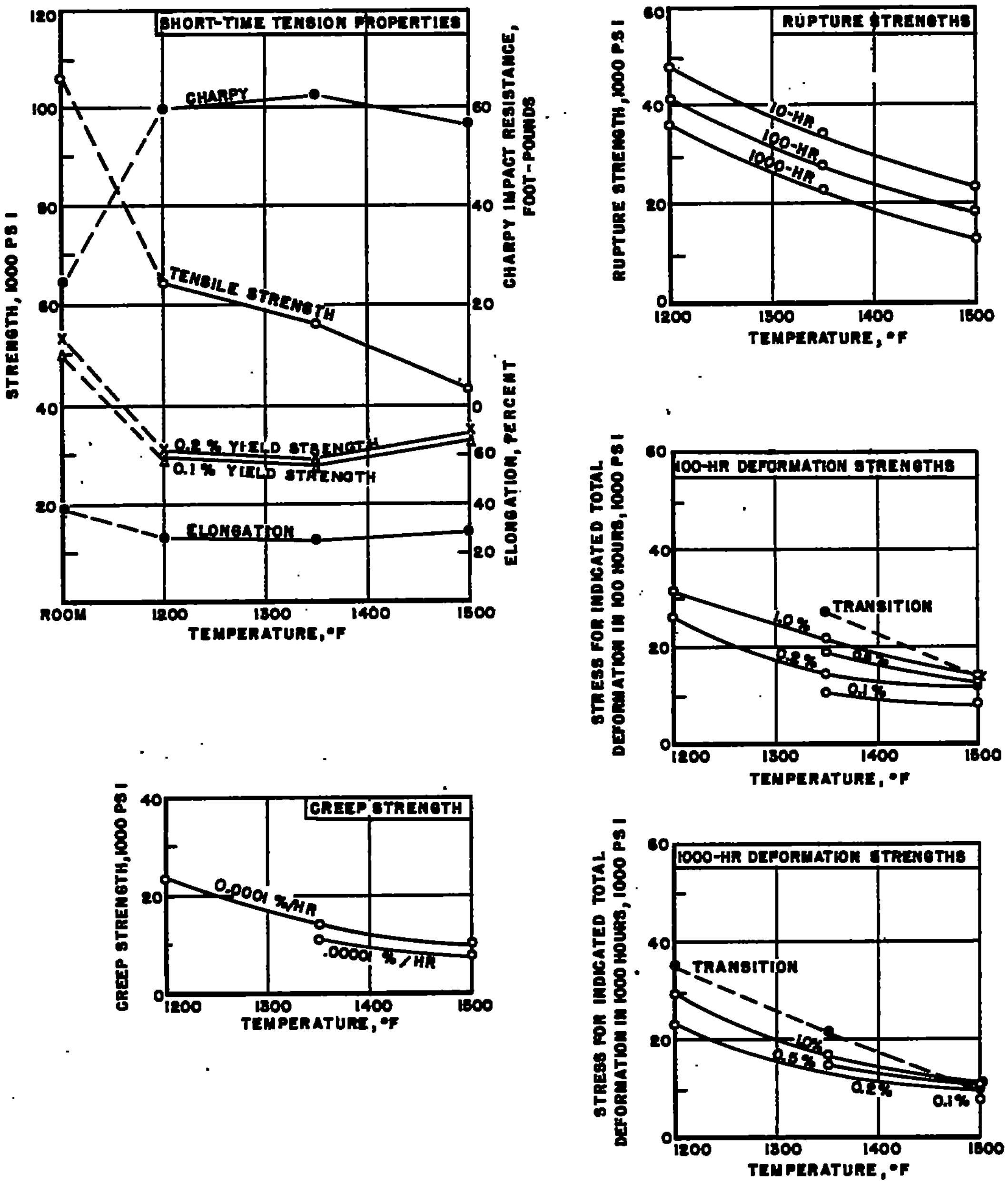
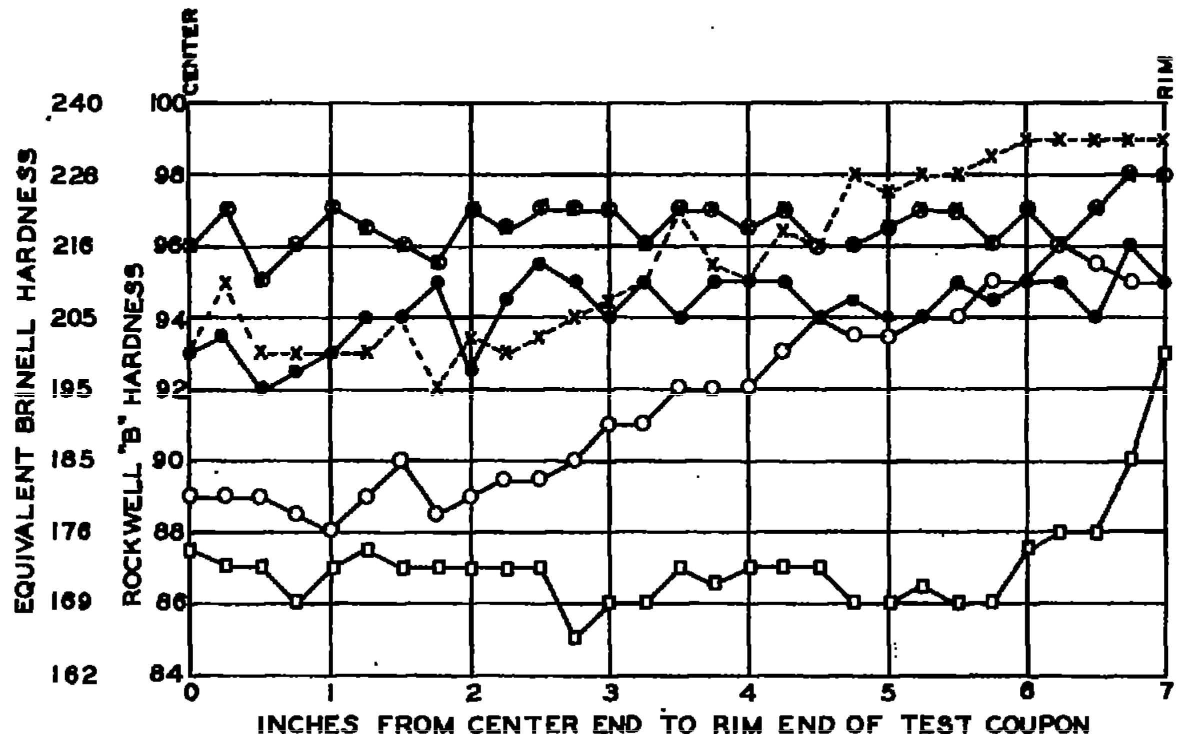


FIGURE 4.- SUMMARY OF THE PROPERTIES OF THE LOW-CARBON N-155 ALLOY DISC, NR-66E-2R. (TESTED AS WATER-QUENCHED FROM 2200°F AND AGED 24 HOURS AT 1350°F.)



SYMBOL	DISC	COUPON	TREATMENT
O	NR66E-1L	1A3	AS FORGED
X	NR66E-1R	1I3	AS FORGED + 1500° F 24 HR
●	NR66E-2L	2A3	2200° F W.Q.+ 1500° F 24 HR
□	NR66E-2R	2I3	2200° F W.Q.+ 1350° F 24 HR
●	NR66E-3L	3A3	2250° F W.Q.+ 3% COLD WORK AT 1200° F+1500° F 24 HR

FIGURE 5.- VARIATION IN HARDNESS FROM CENTER TO RIM OF CENTER PLANE; COUPONS OF LOW-CARBON N155 ALLOY DISCS, NR66E.

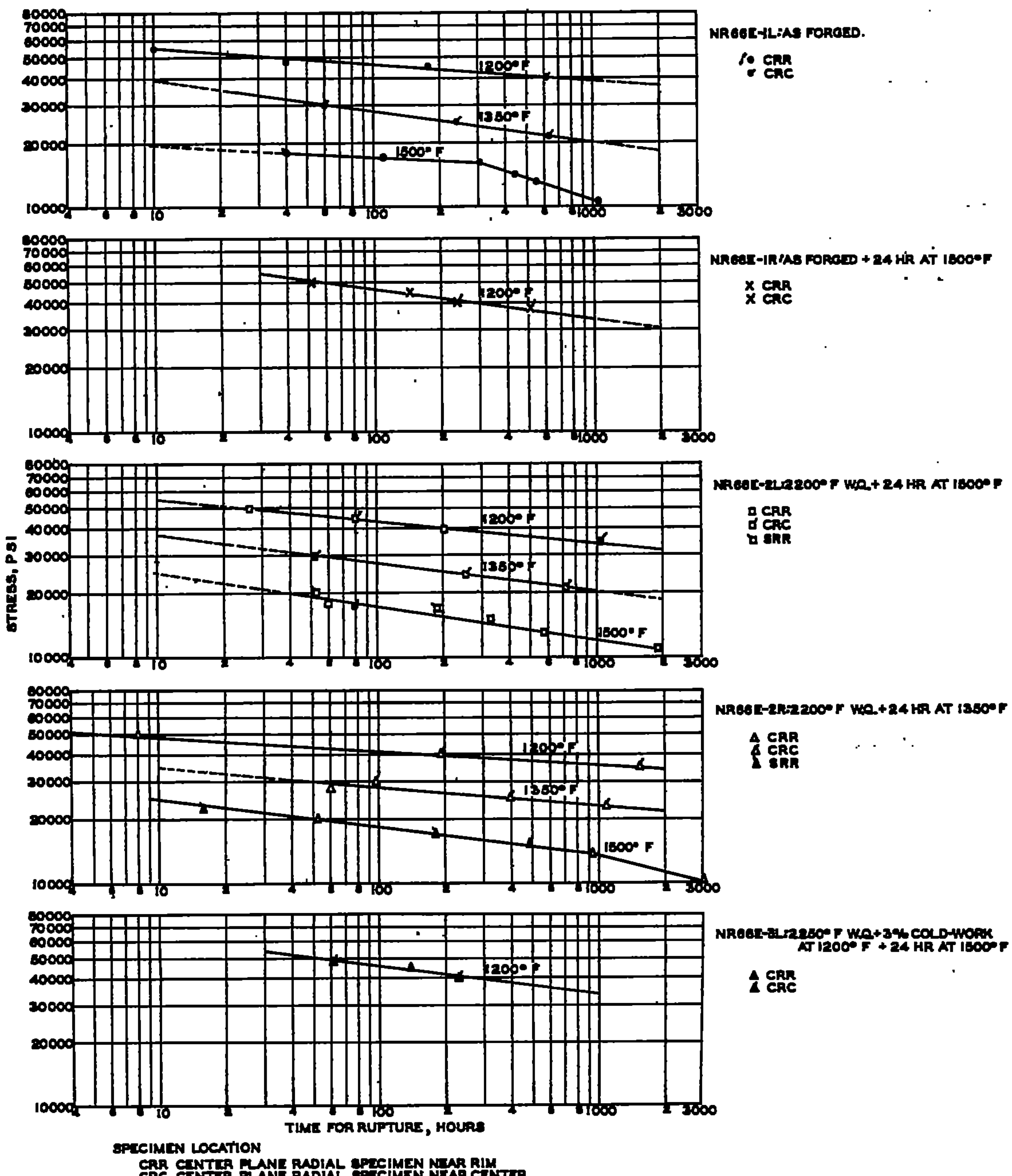


FIGURE 6.-STRESS-RUPTURE-TIME CURVES AT 1200°, 1350°, AND 1500° F FOR LOW-CARBON N155 ALLOY DISCS, NR66E.

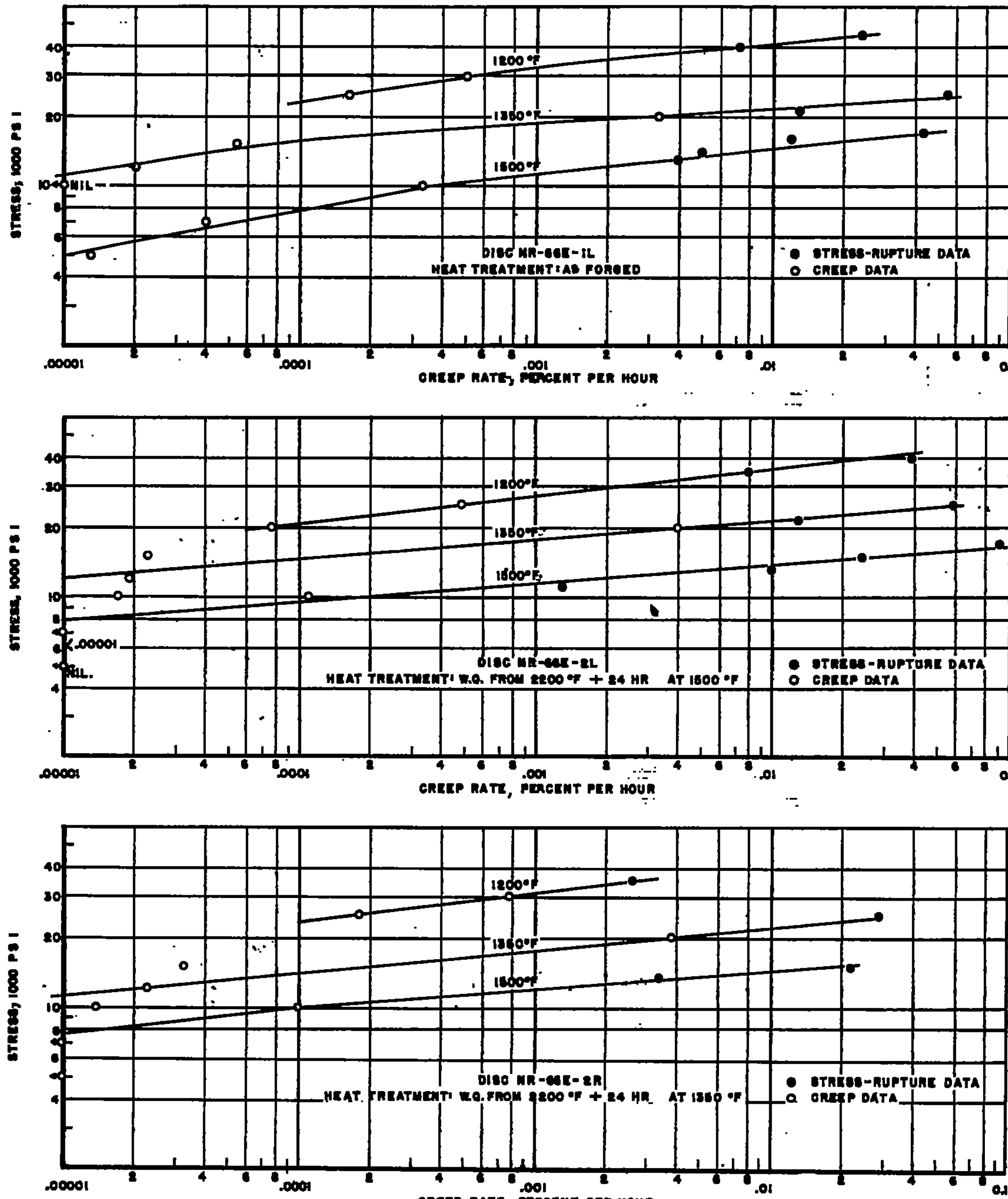
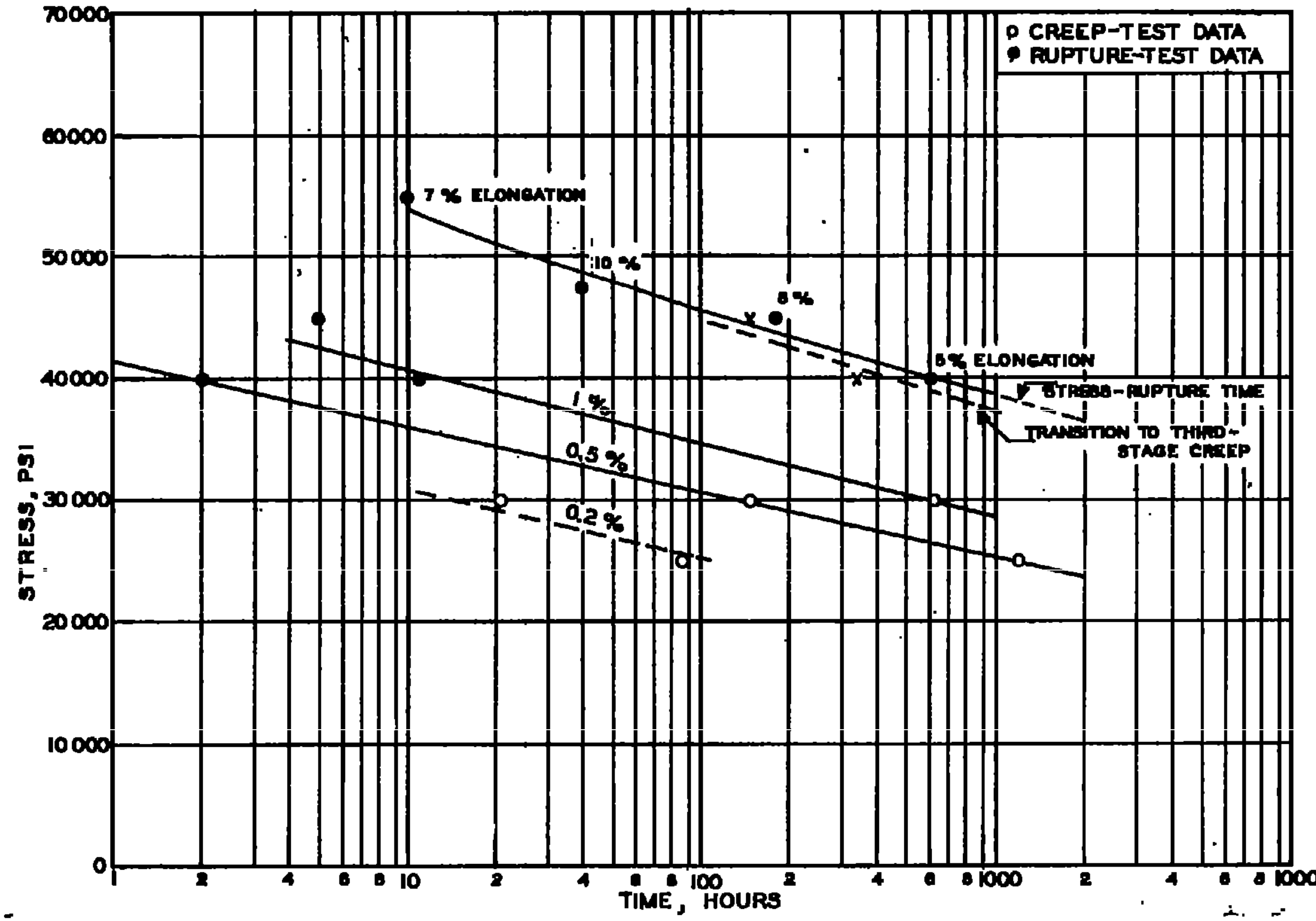
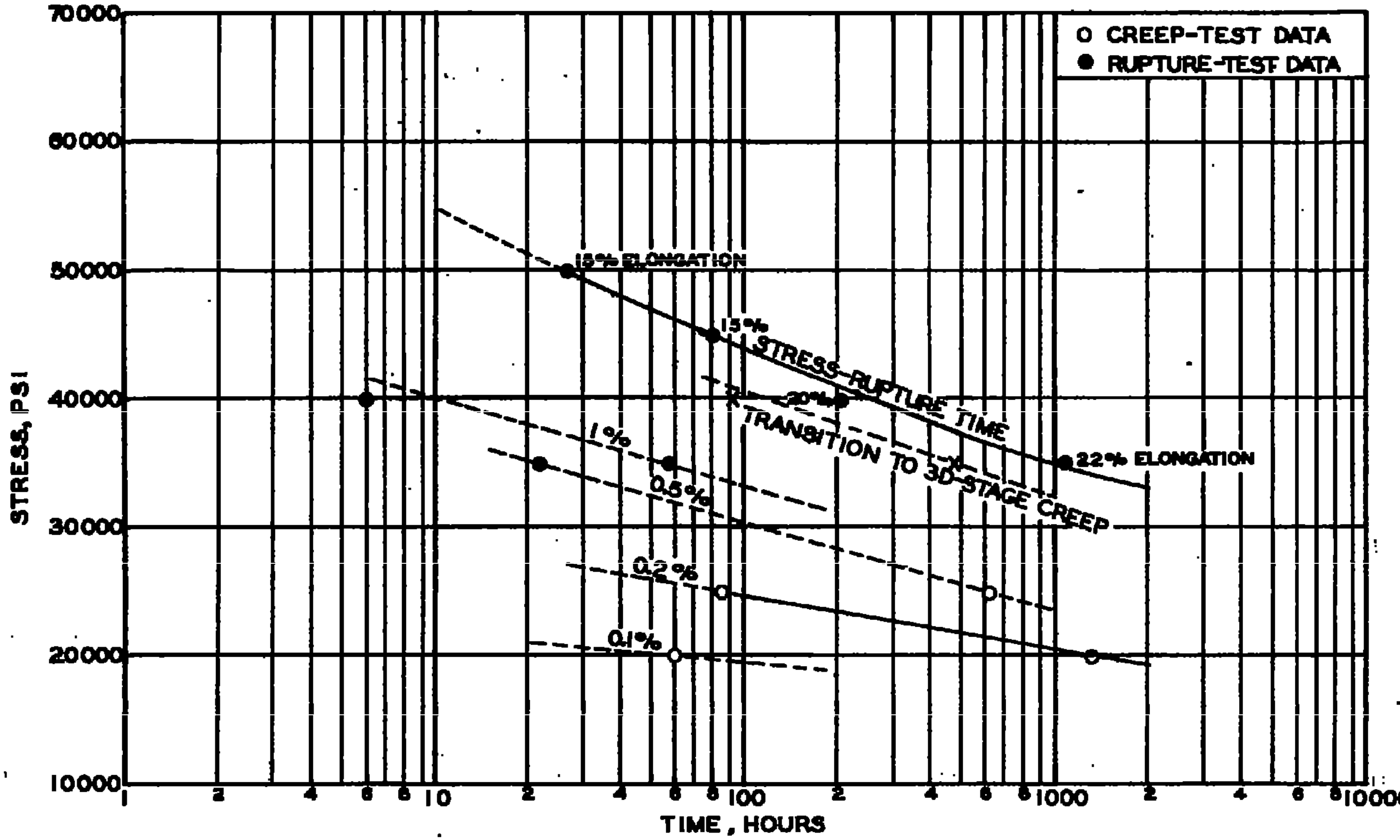


FIGURE 7.- STRESS-CREEP-RATE CURVES FOR LOW-CARBON N-155 ALLOY DISCS, NR-66E.



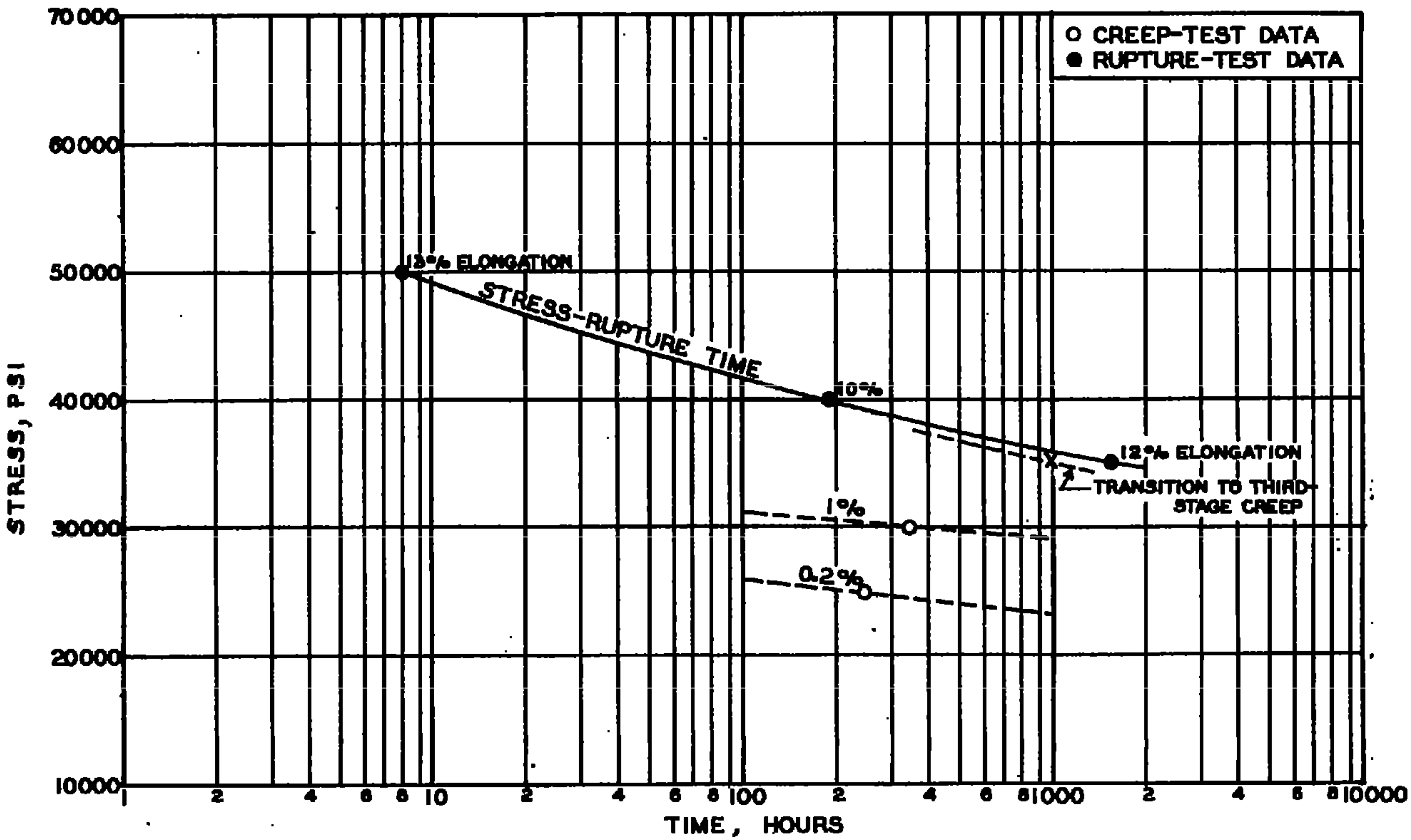
HEAT TREATMENT: AS FORGED

FIGURE 8.–STRESS–TIME FOR TOTAL DEFORMATION CURVES AT 1200° F FOR LOW–CARBON N155 ALLOY DISC, NR66E–IL.



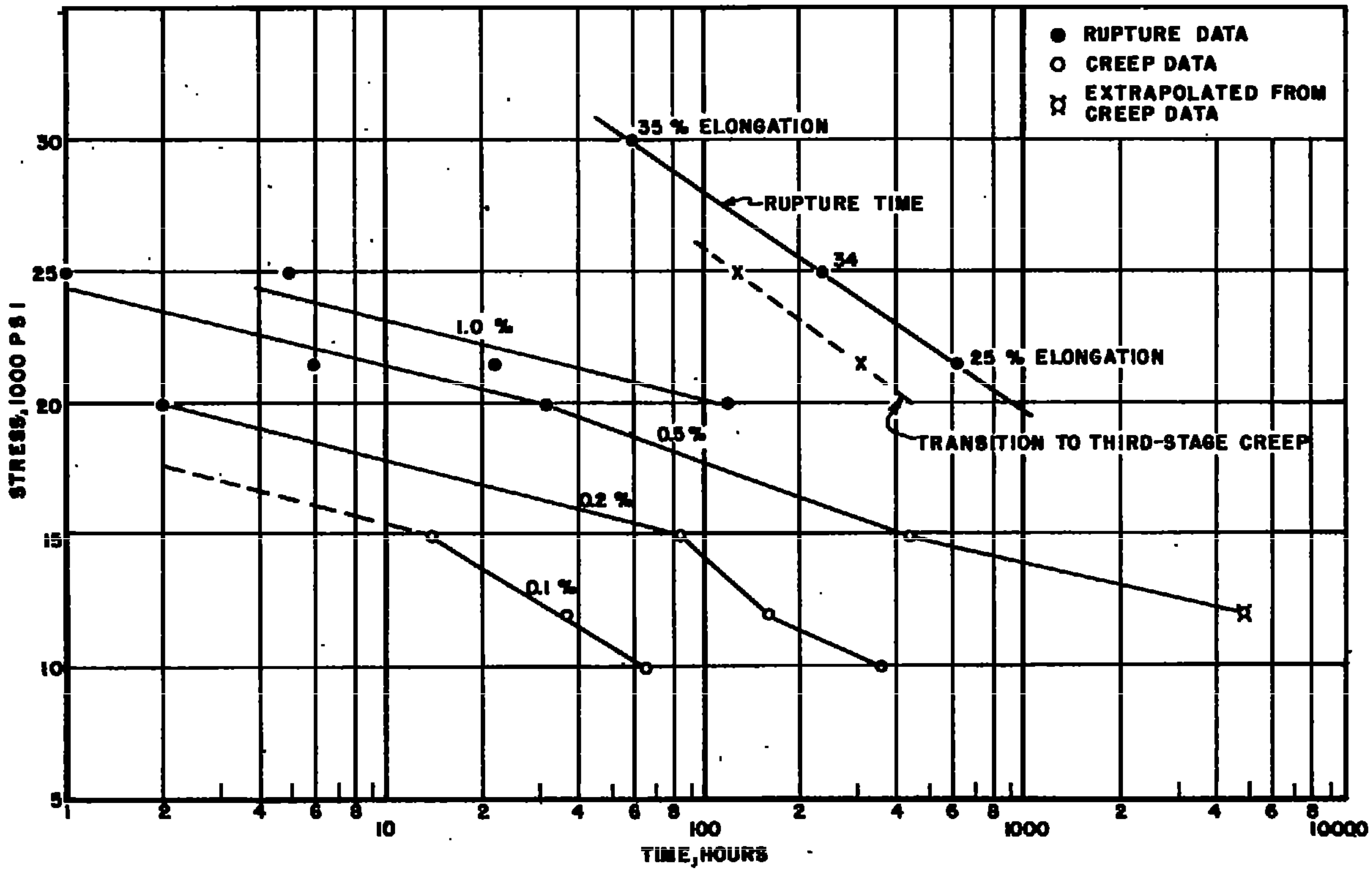
HEAT TREATMENT: W.Q. FROM 2200° F + AGED 24 HOURS AT 1500° F

FIGURE 9.–STRESS–TIME FOR TOTAL DEFORMATION CURVES AT 1200° F FOR LOW–CARBON N-155 ALLOY DISC, NR-66E-2L.



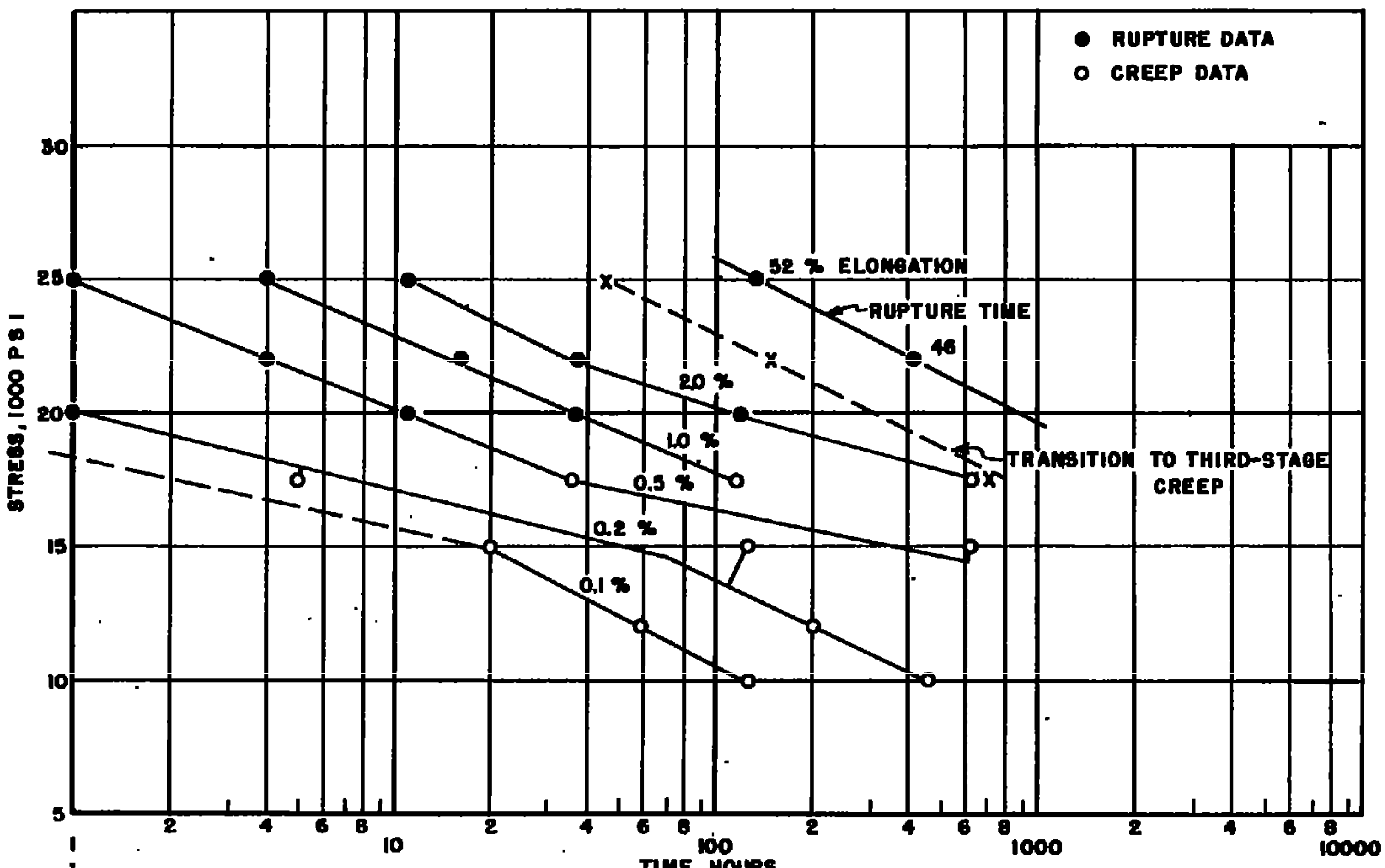
HEAT TREATMENT: W.Q. FROM 2200° F + AGED 24 HOURS AT 1350° F

FIGURE 10.—STRESS-TIME FOR TOTAL DEFORMATION CURVES AT 1200° F FOR LOW-CARBON N155 ALLOY DISC, NR66E-2R.



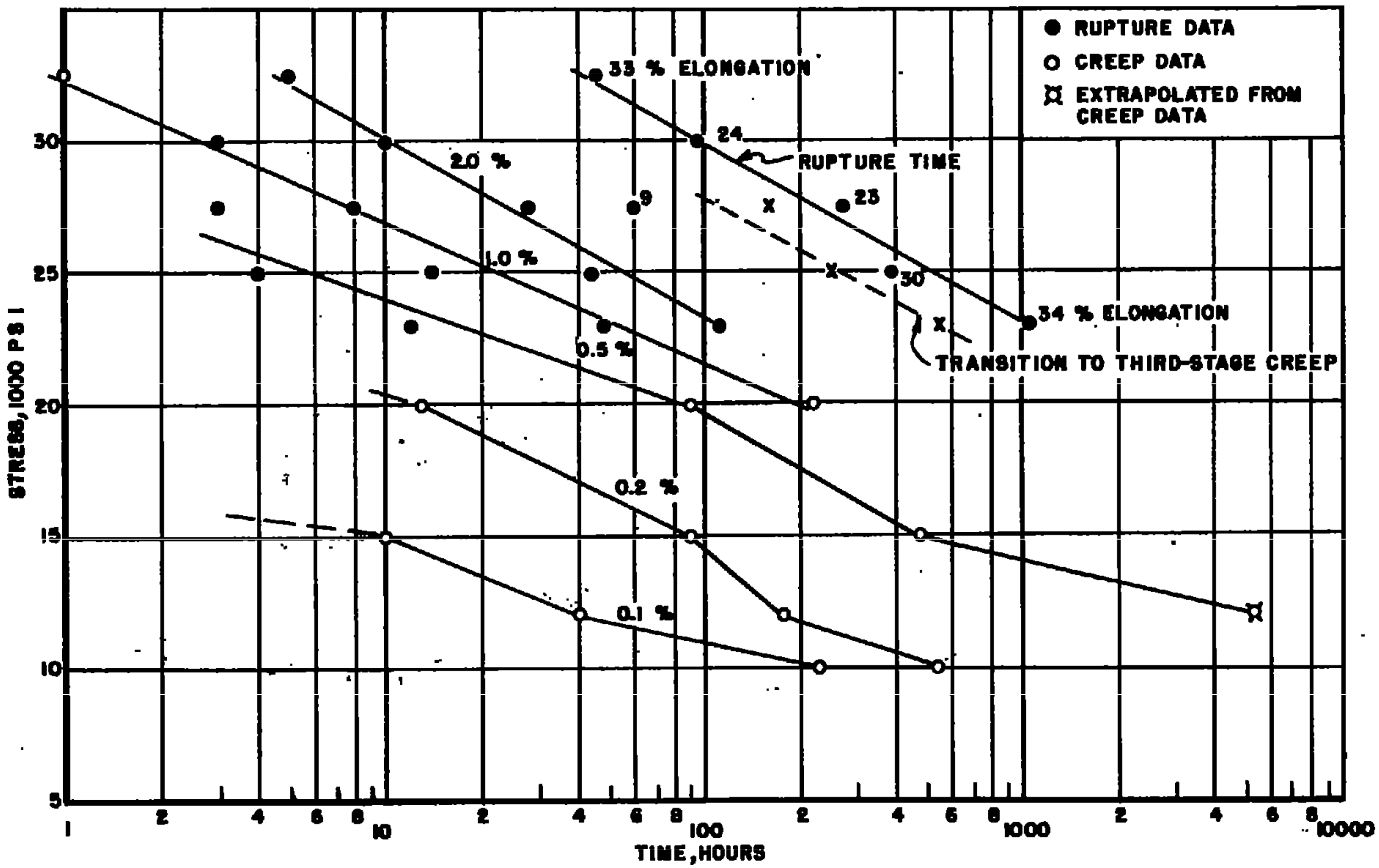
HEAT TREATMENT: AS FORGED

FIGURE 11.–STRESS VS. TIME FOR TOTAL DEFORMATION CURVES AT 1350 °F FOR LOW-CARBON N-155 ALLOY DISC, NR-66E-1L.



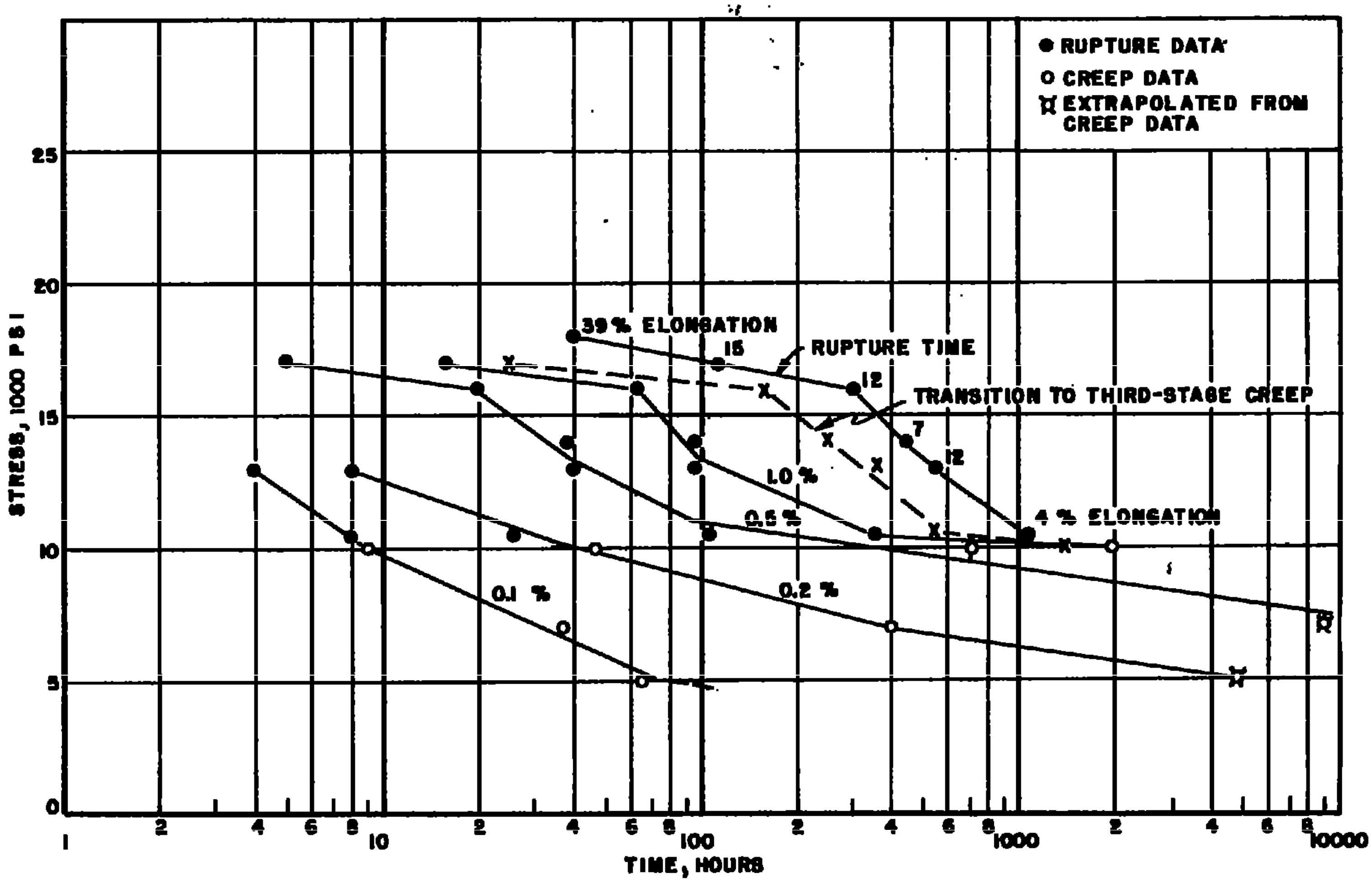
HEAT TREATMENT: W.Q. FROM 2200 °F + 24 HOURS AT 1500 °F

FIGURE 12.— STRESS VS. TIME FOR TOTAL DEFORMATION CURVES AT 1350 °F FOR LOW-CARBON N-155 ALLOY DISC, NR-66E-2L.



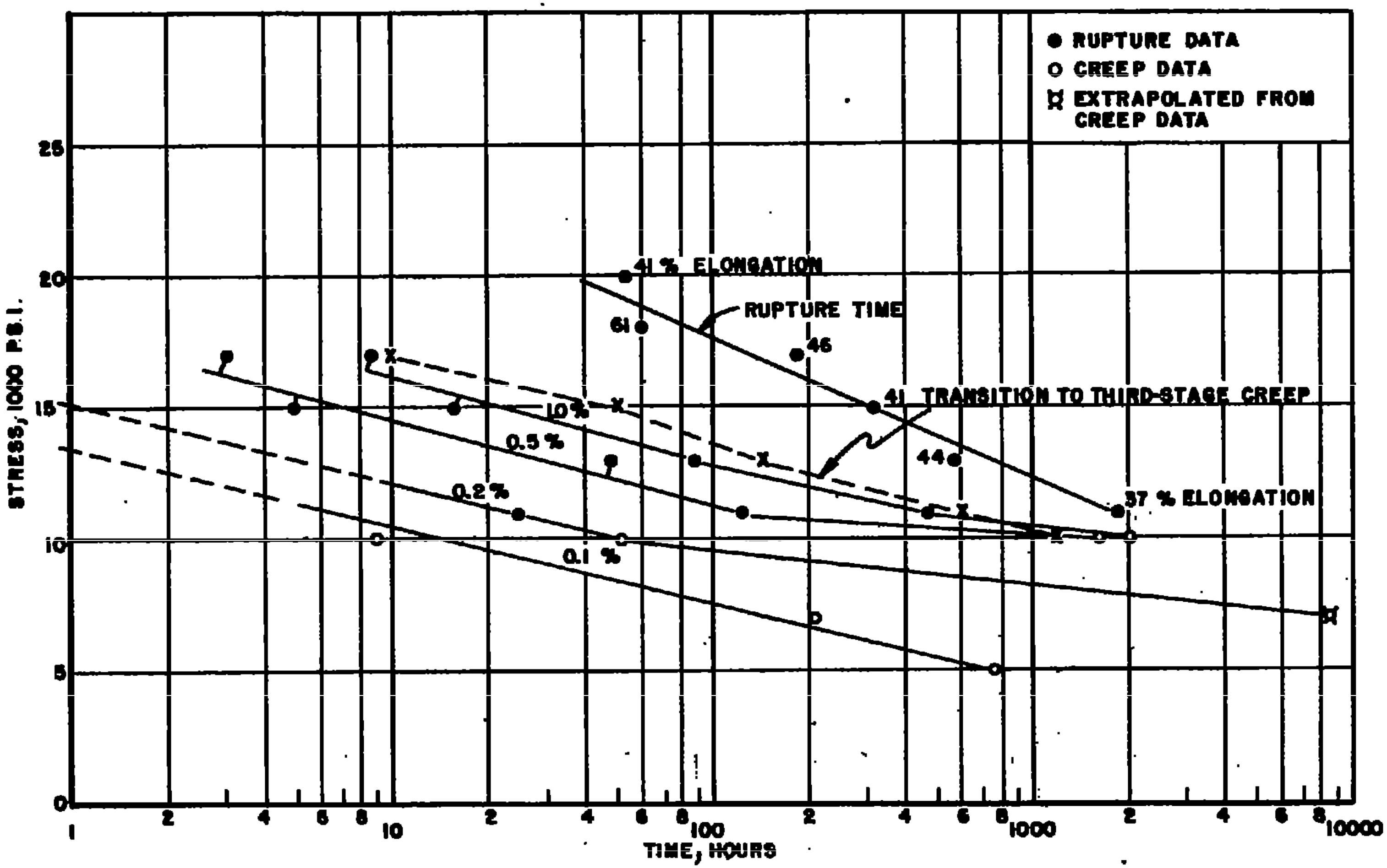
HEAT TREATMENT: W.Q. FROM 2200° F + 24 HOURS AT 1350° F

FIGURE 13.-STRESS VS. TIME FOR TOTAL DEFORMATION CURVES AT 1350 °F FOR LOW-CARBON N-155 ALLOY DISC, NR-66E-2R.



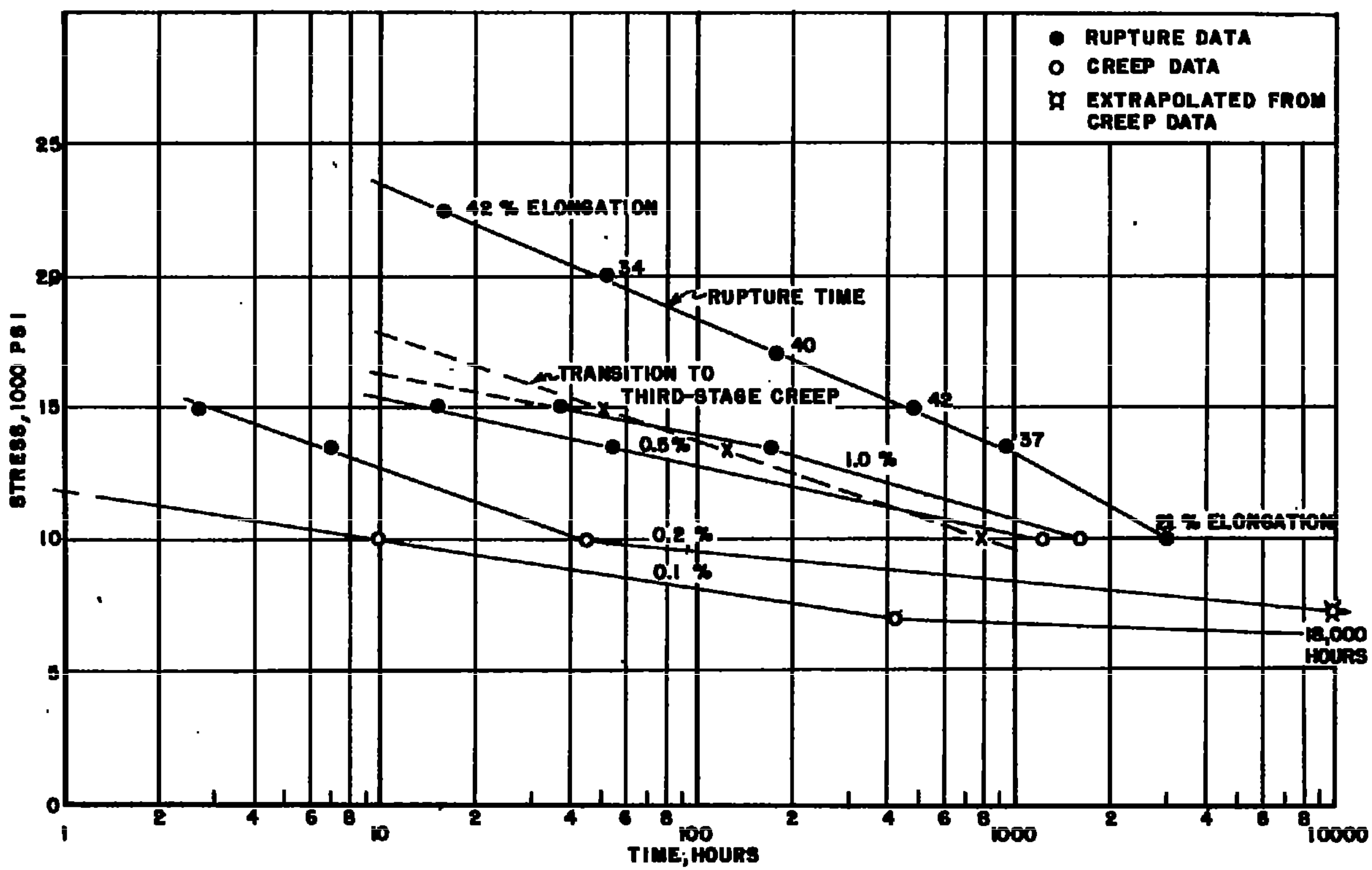
HEAT TREATMENT: AS FORGED

FIGURE 14.- STRESS VS. TIME FOR TOTAL DEFORMATION CURVES AT 1500 °F FOR LOW-CARBON N-155 ALLOY DISC, NR-66E -IL.



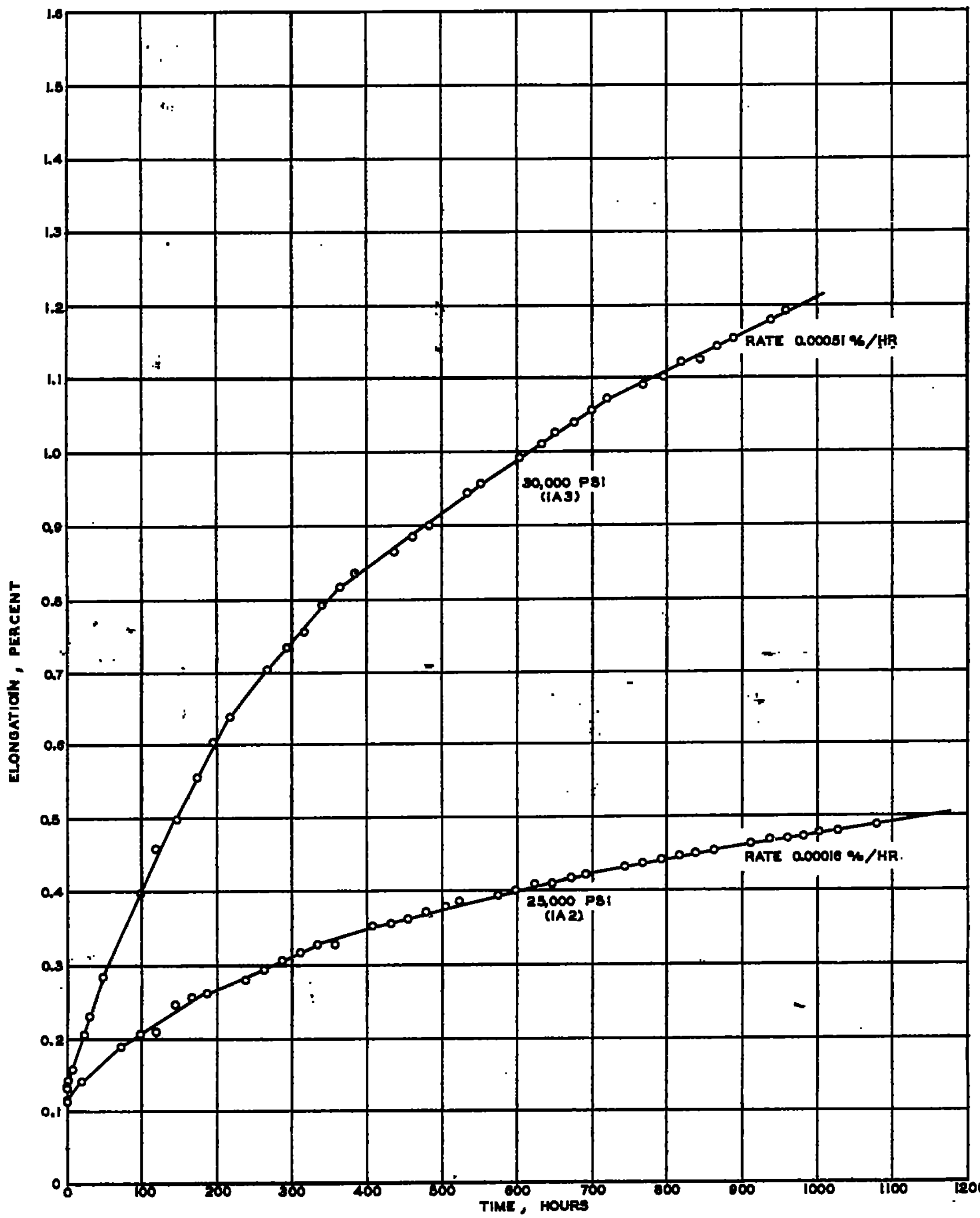
HEAT TREATMENT: W.Q. FROM 2200 °F + 24 HOURS AT 1500 °F

FIGURE 15.- STRESS VS. TIME FOR TOTAL DEFORMATION CURVES AT 1500 °F FOR LOW-CARBON N-155 ALLOY DISC, NR-66E-2L.



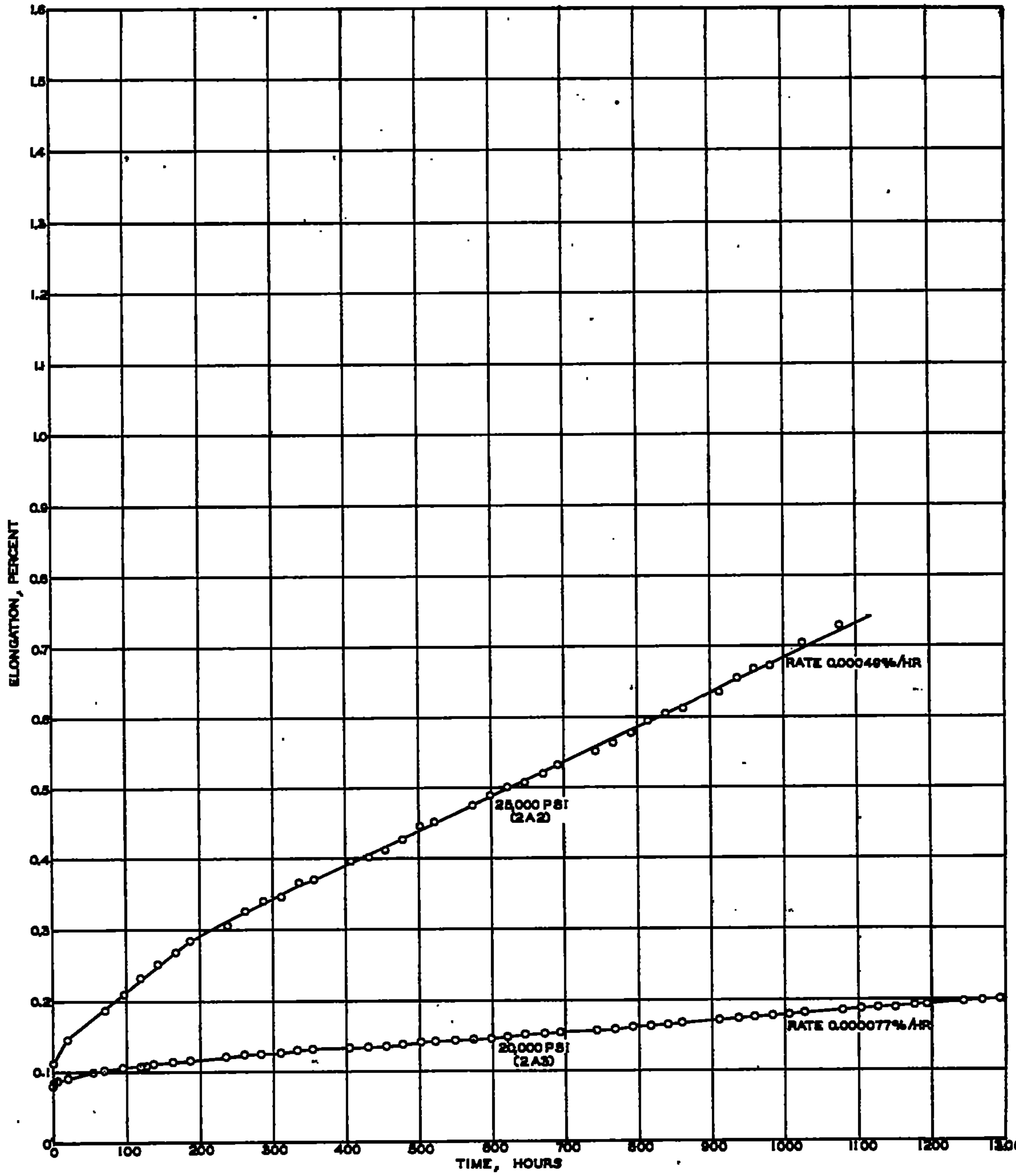
HEAT TREATMENT: W.Q. FROM 2200 °F + 24 HOURS AT 1350 °F

FIGURE 16.–STRESS VS. TIME FOR TOTAL DEFORMATION CURVES AT 1500 °F FOR LOW-CARBON N-155 ALLOY DISC, NR-66E-2R.



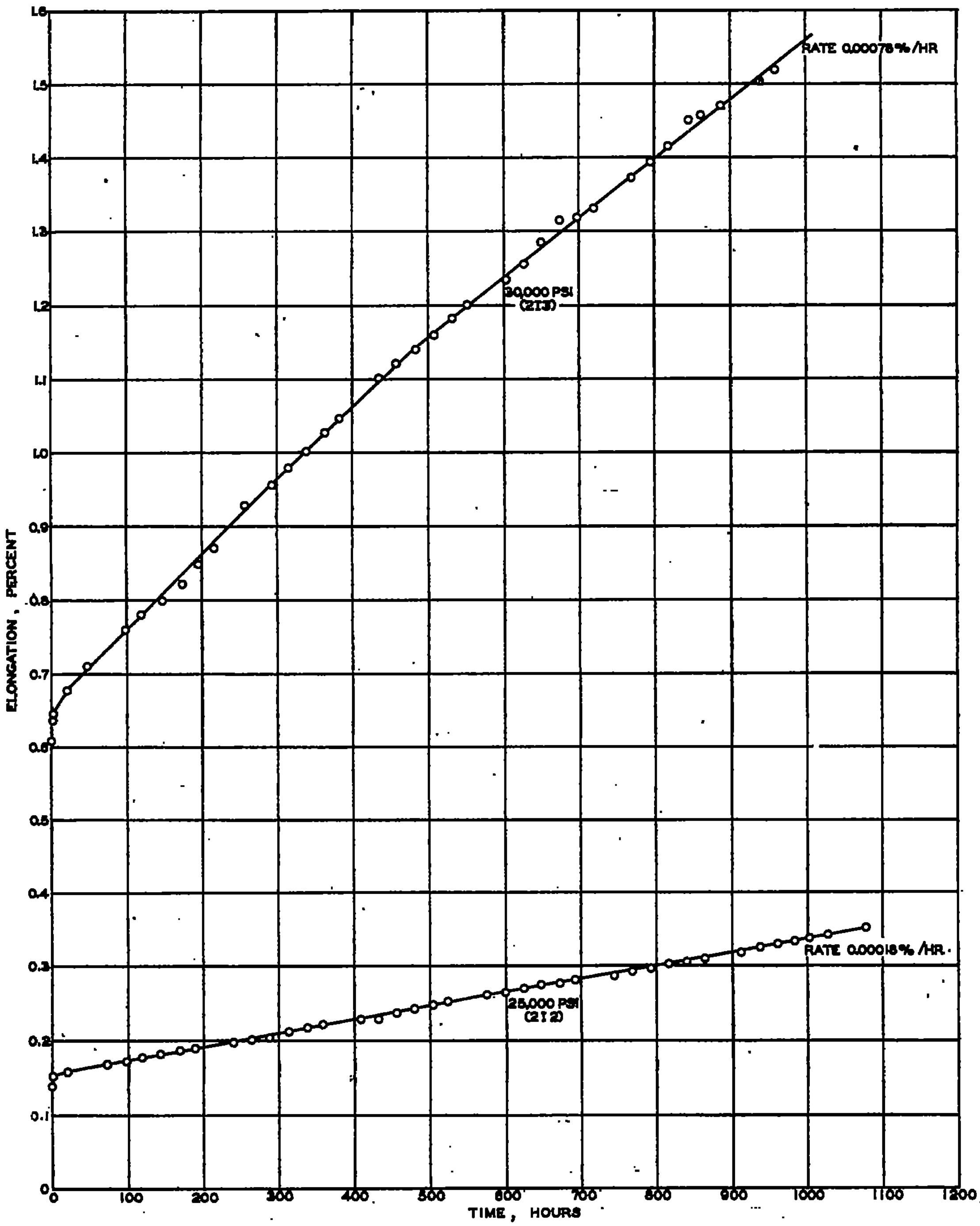
HEAT TREATMENT:- AS FORGED

FIGURE 17.—TIME-ELONGATION CURVES AT 1200° F FOR LOW-CARBON N-155 DISC, NR66E-1L.



HEAT TREATMENT:- WATER QUENCHED FROM 2200° F + AGED FOR 24 HOURS AT 1500° F

FIGURE 18.-TIME-ELONGATION CURVES AT 1200° F FOR LOW-CARBON N155 DISC, NR66E-2L.



HEAT TREATMENT-WATER QUENCHED FROM 2200° F + AGED FOR 24 HOURS AT 1350° F.

FIGURE 19.—TIME-ELONGATION CURVES AT 1200° F FOR LOW-CARBON N155 DISC, NR66E-2R.

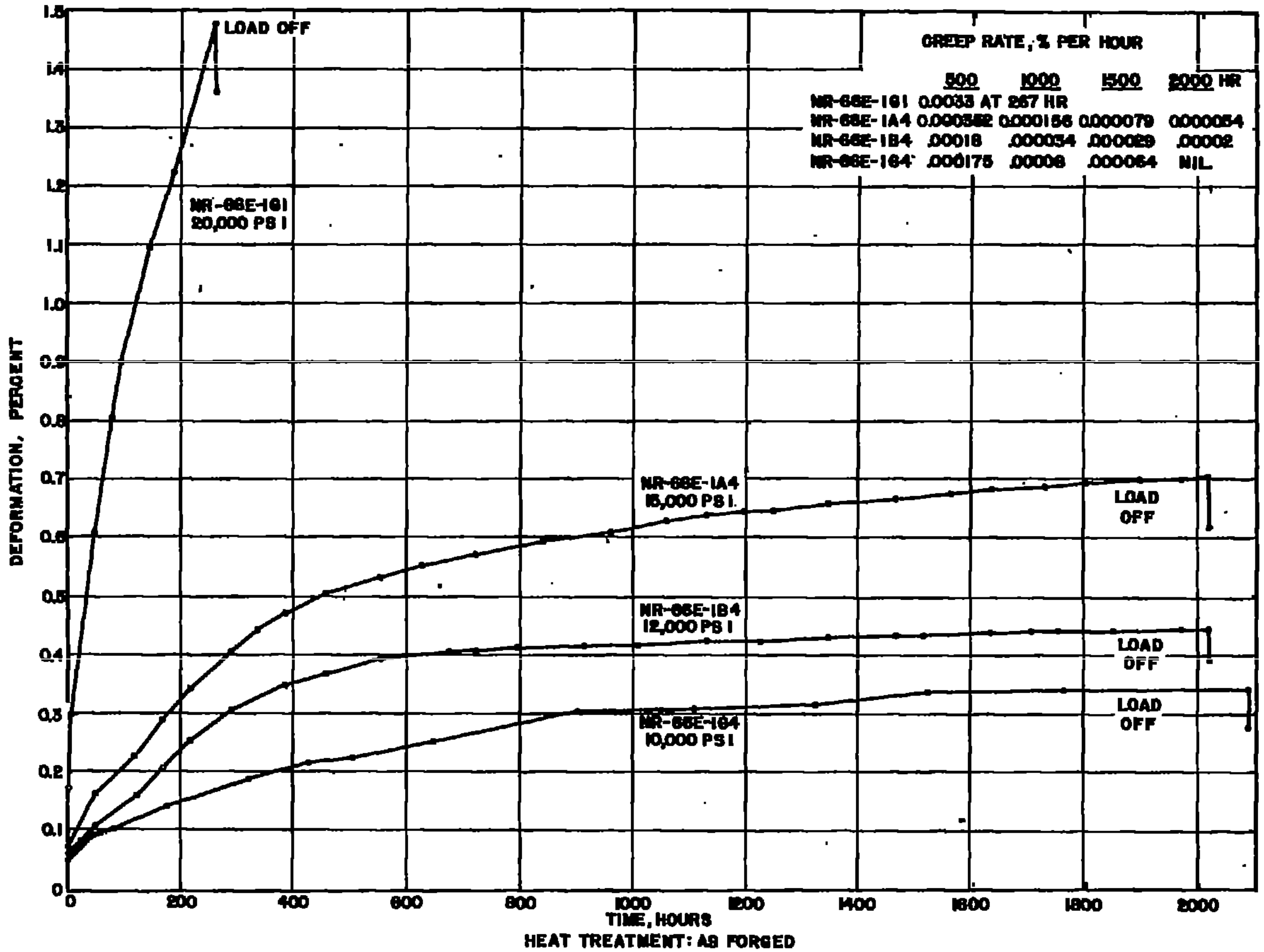


FIGURE 20.-TIME-DEFORMATION CURVES AT 1350°F FOR LOW-CARBON N-155 ALLOY DISC, NR-66E-1L.

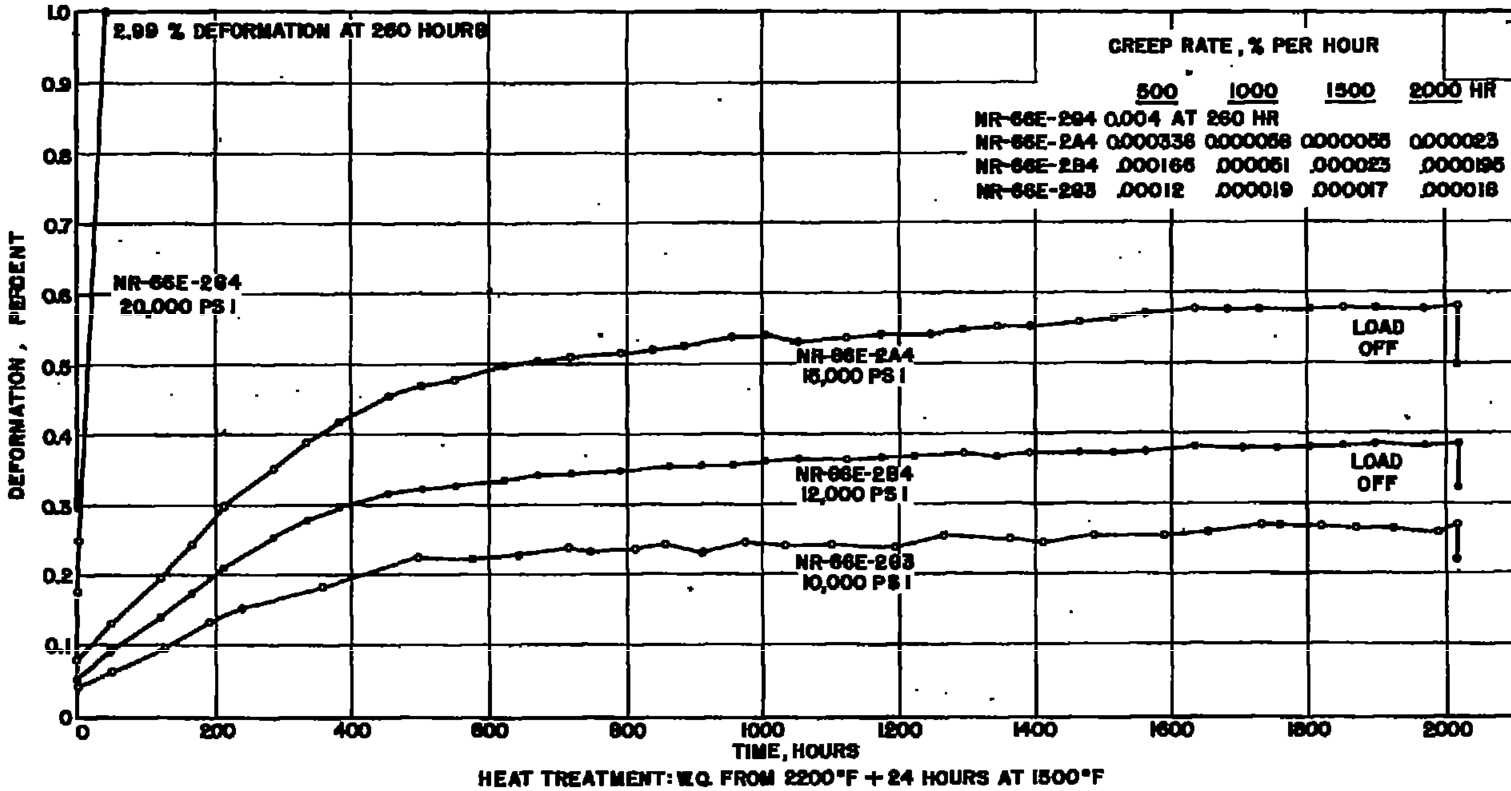
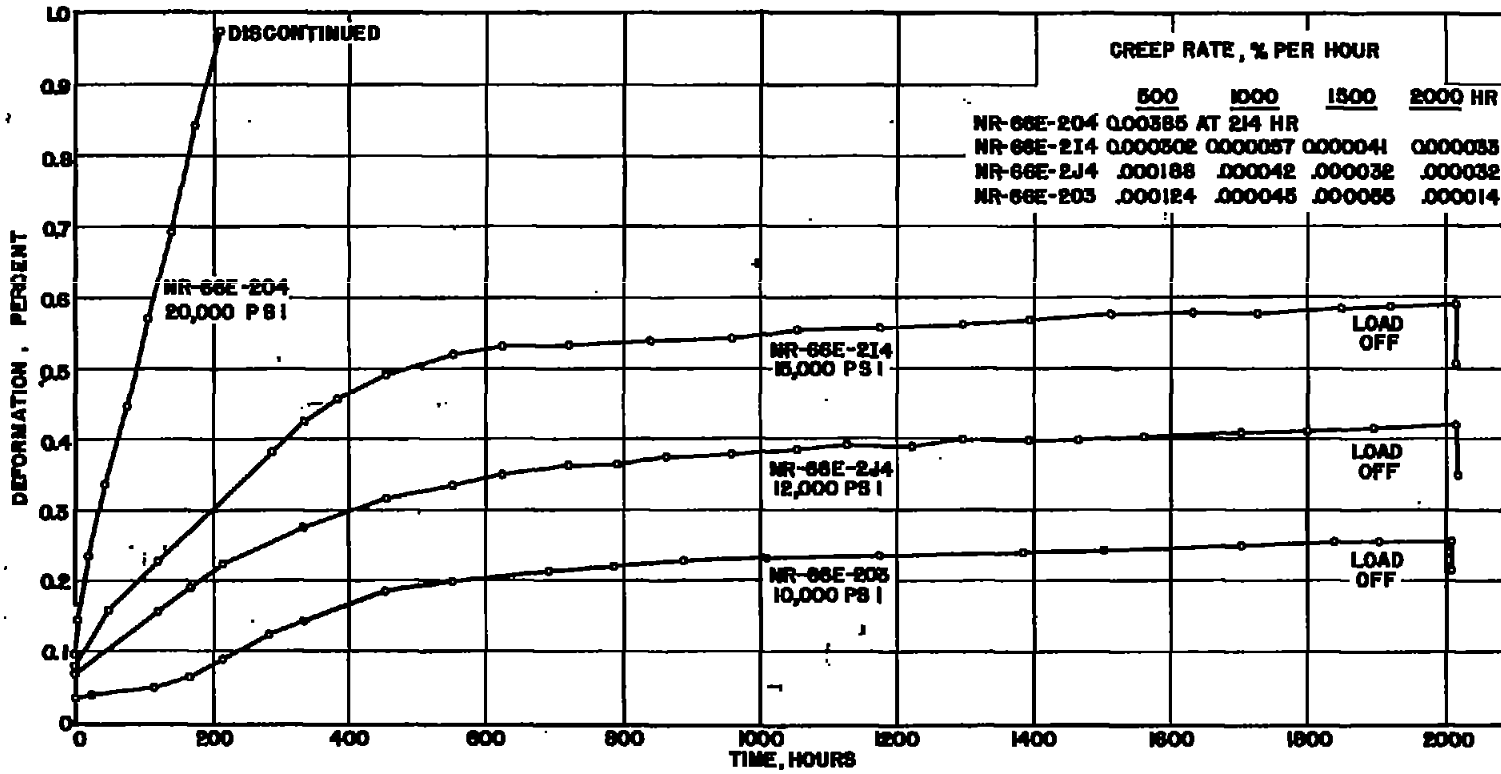


FIGURE 21—TIME-DEFORMATION CURVES AT 1350°F FOR LOW-CARBON N-155 ALLOY DISC, NR-66E-2L.



HEAT TREATMENT: W.Q. FROM 2200°F + 24 HOURS AT 1350°F

FIGURE 22.- TIME-DEFORMATION CURVES AT 1350°F FOR LOW-CARBON N-155 ALLOY DISC, NR-66E-2R.

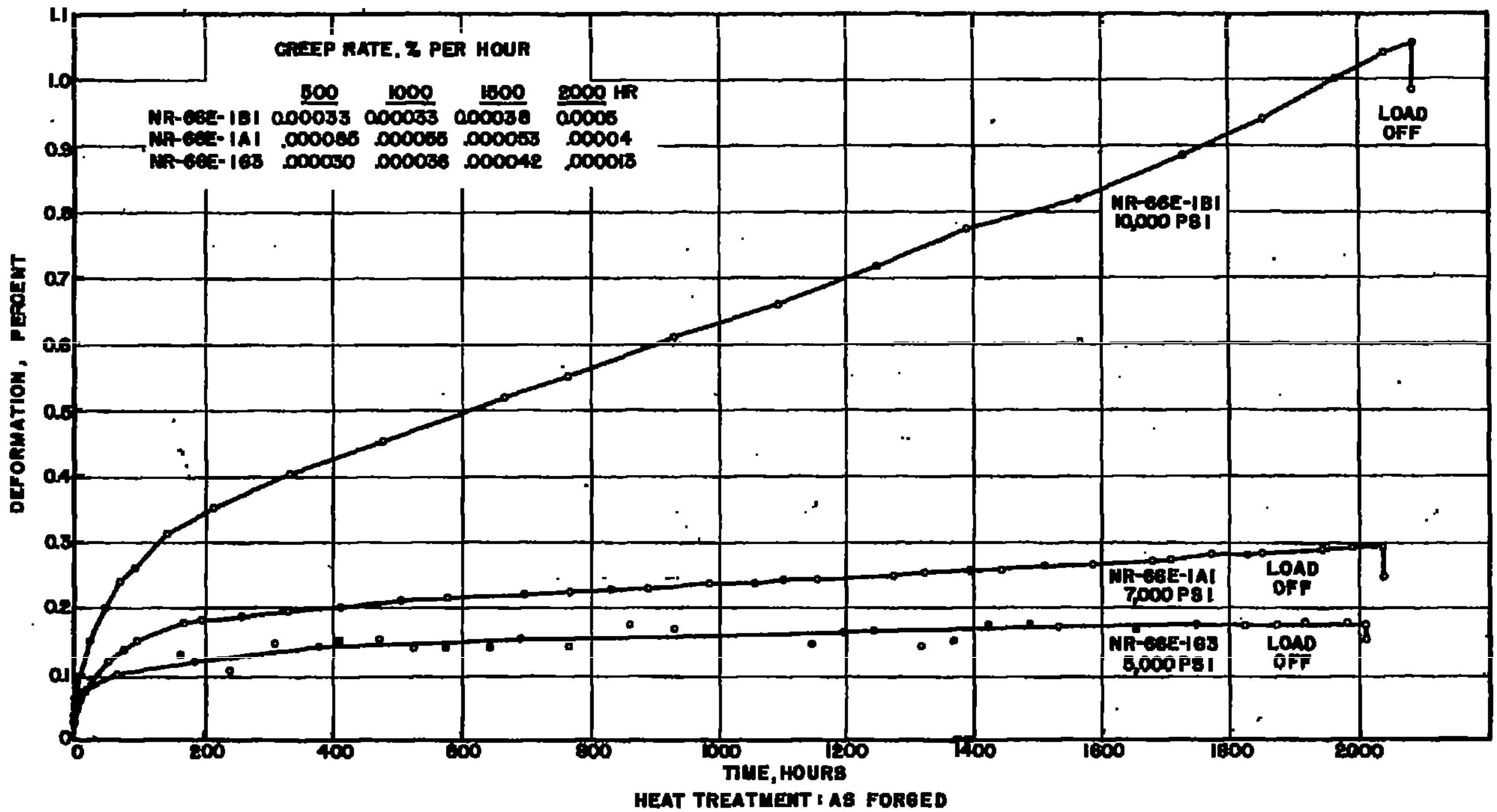
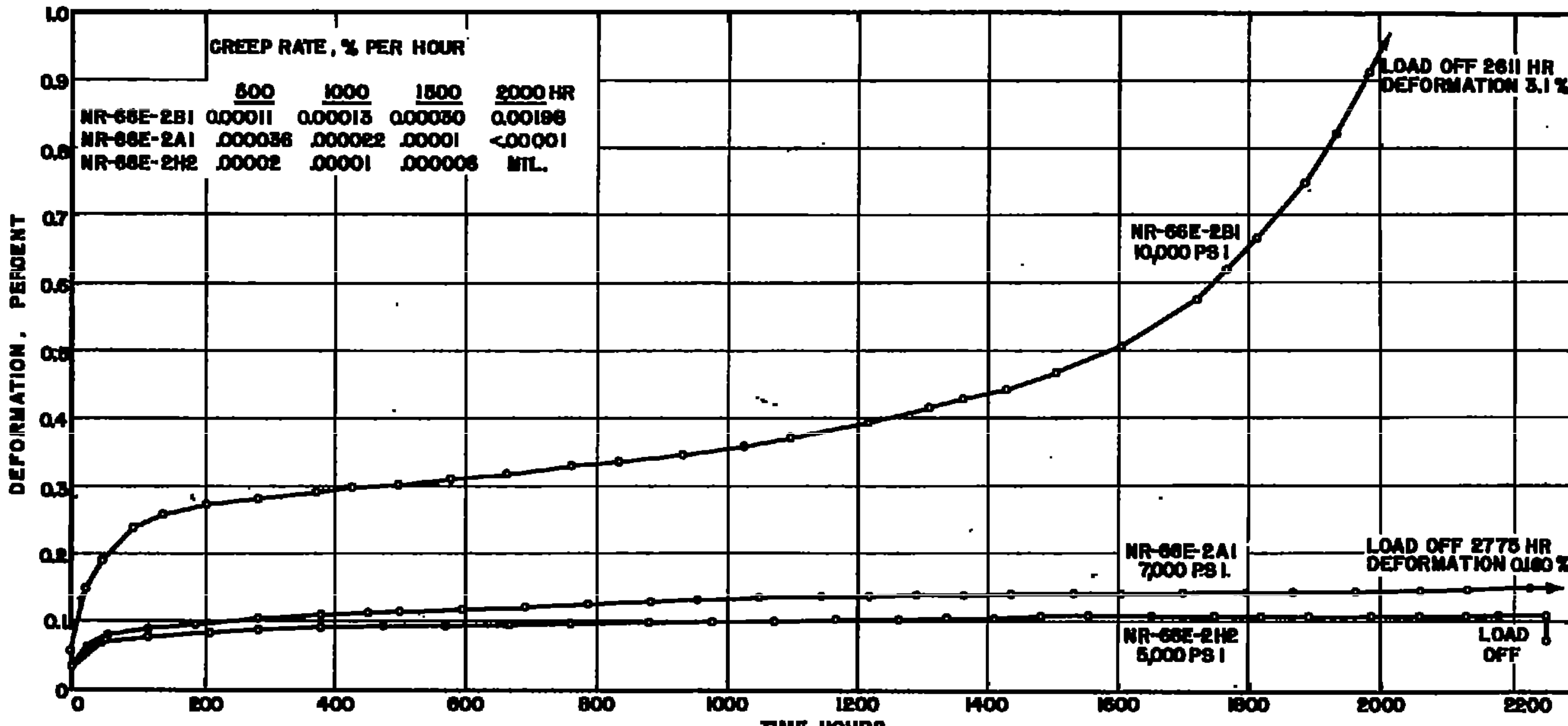


FIGURE 23.–TIME-DEFORMATION CURVES AT 1500°F FOR LOW-CARBON N-155 ALLOY DISC, NR-66E-1L.



HEAT TREATMENT: W.Q. FROM 2200°F + 24 HOURS AT 1500°F

FIGURE 24.-TIME-DEFORMATION CURVES AT 1500 °F FOR LOW-CARBON N-155 ALLOY DISC, NR-66E-2L.

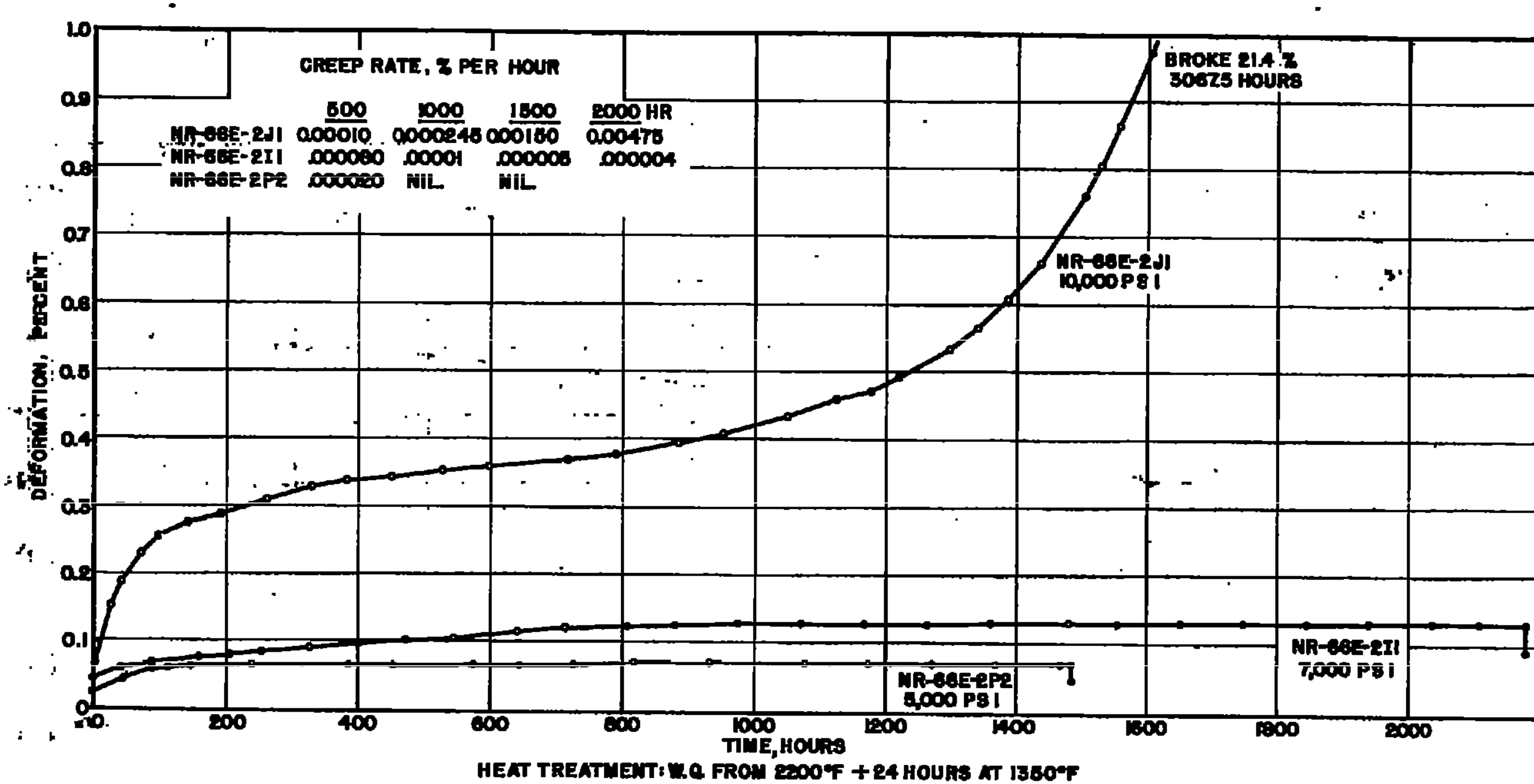
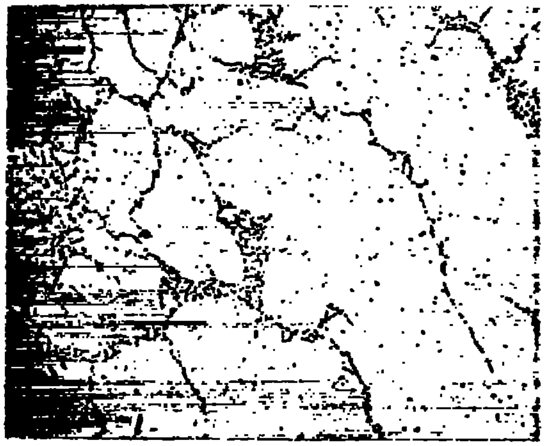
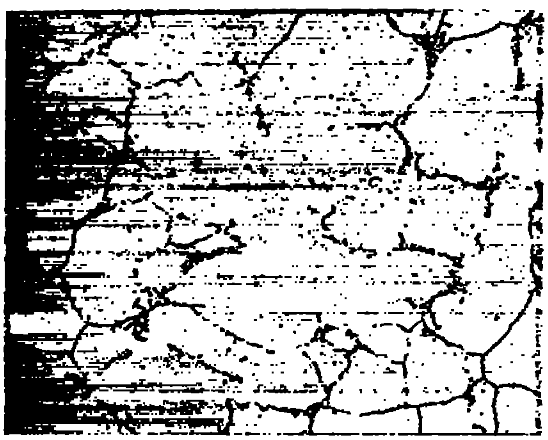


FIGURE 25.—TIME-DEFORMATION CURVES AT 1500°F FOR LOW-CARBON N-155 ALLOY DISC, NR-66E-2R.



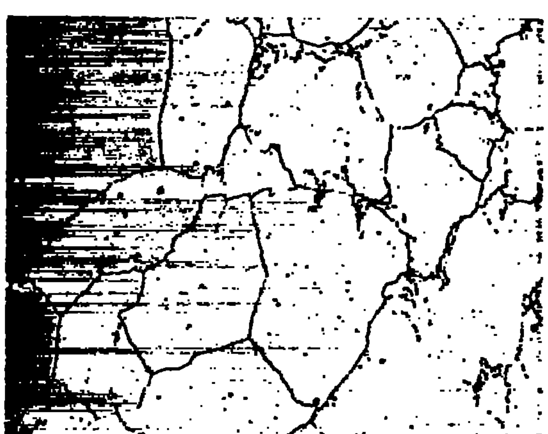
100X 1000X

Disc NR-66E-1L - As forged.



100X 1000X

Disc NR-66E-2L - Water quenched from 2200° F + 24 hours at 1500° F.

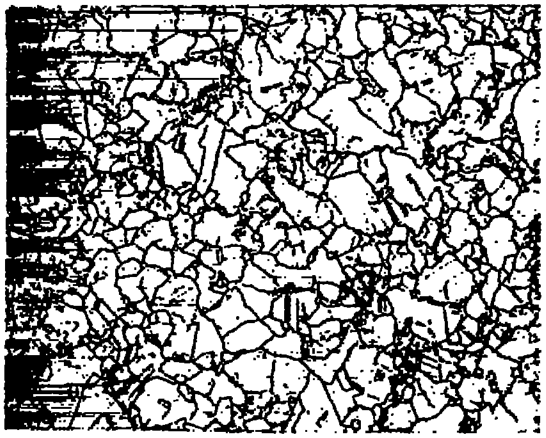


100X 1000X

Disc NR-66E-2R - Water quenched from 2200° F + 24 hours at 1350° F.

Electrolytic chromic acid etch

FIGURE 26.- ORIGINAL MICROSTRUCTURES FROM THE CENTER SECTIONS OF THE LOW-CARBON N-155 DISCS, NR-66E.



100X

1000X

Specimen 1A3 - 960 hours at 1200° F and 30,000 psi.

100X

1000X

Specimen 1B4 - 2015 hours at 1350° F and 12,000 psi.

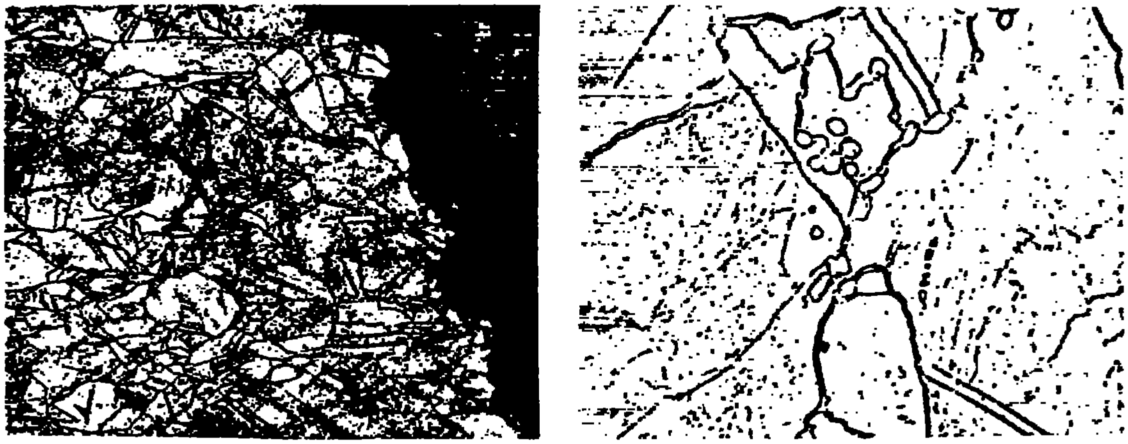
100X

1000X

Specimen 1A1 - 2037 hours at 1500° F and 7000 psi.

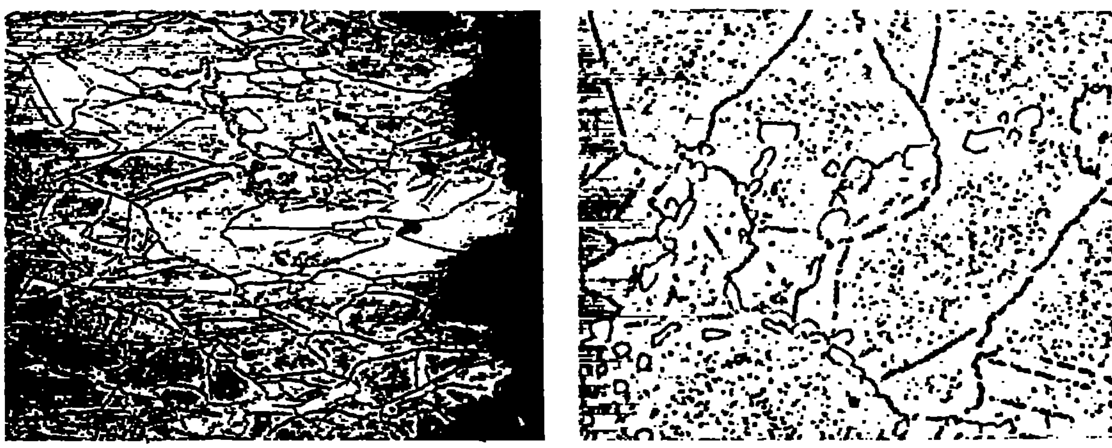
Electrolytic chromic acid etch

FIGURE 27.- MICROSTRUCTURE OF SPECIMENS FROM LOW-CARBON N-155 ALLOY DISC, NR-66E-1L, AFTER CREEP TESTS. TESTED AS FORGED.



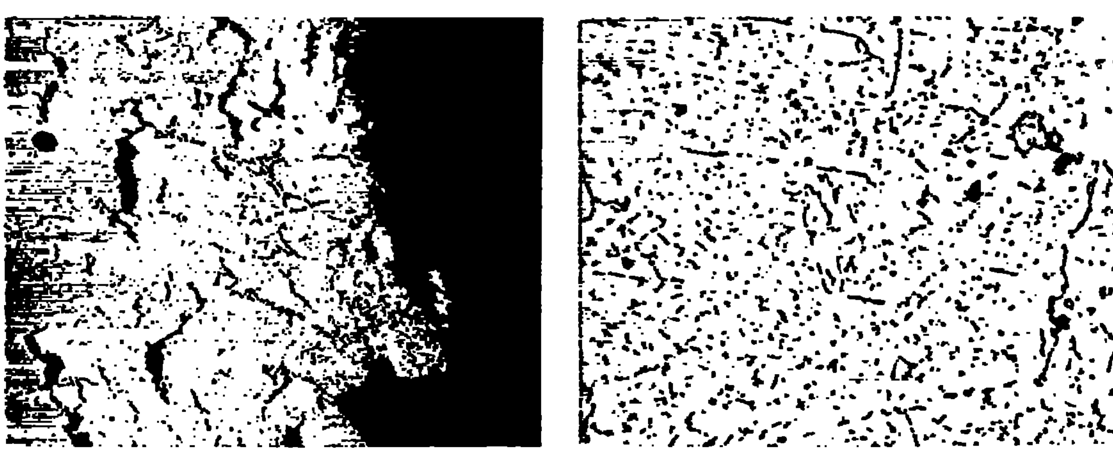
100X 1000X

Specimen 1C5 - 613 hours for rupture at 1200° F and 40,000 psi.



100X 1000X

Specimen 1D4 - 624 hours for rupture at 1350° F and 21,500 psi.

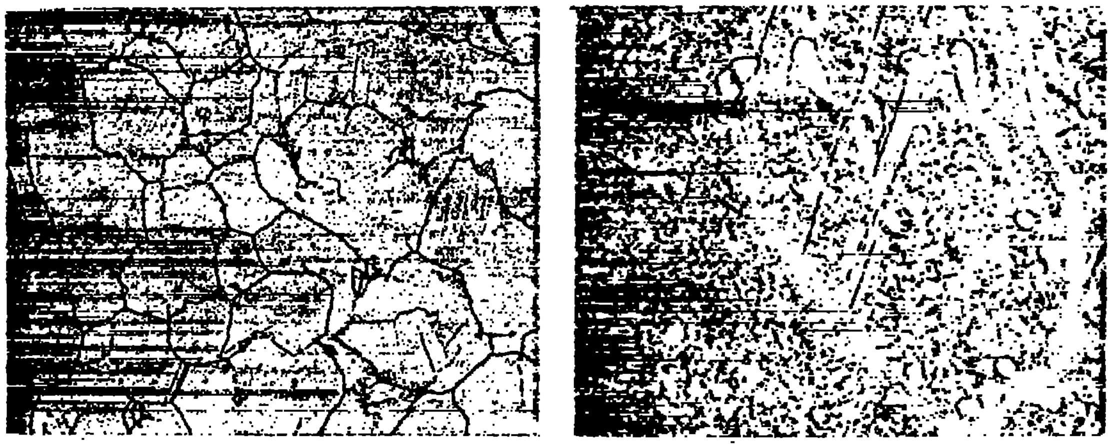


100X 1000X

Specimen 1E4 - 449 hours for rupture at 1500° F and 14,000 psi.

Electrolytic chromic acid etch

FIGURE 28.- MICROSTRUCTURE OF SPECIMENS FROM LOW-CARBON N-155 ALLOY DISC, NR-66E-1L, AFTER STRESS-RUPTURE TESTS. TESTED AS FORGED.

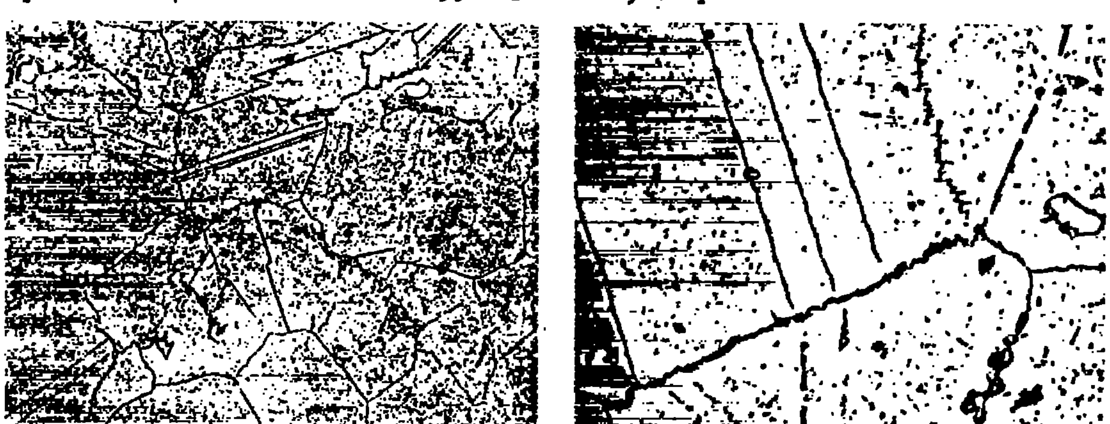


100X 1000X

Specimen 2A2 - 1078 hours at 1200° F and 25,000 psi.

100X 1000X

Specimen 2B4 - 2016 hours at 1350° F and 12,000 psi.

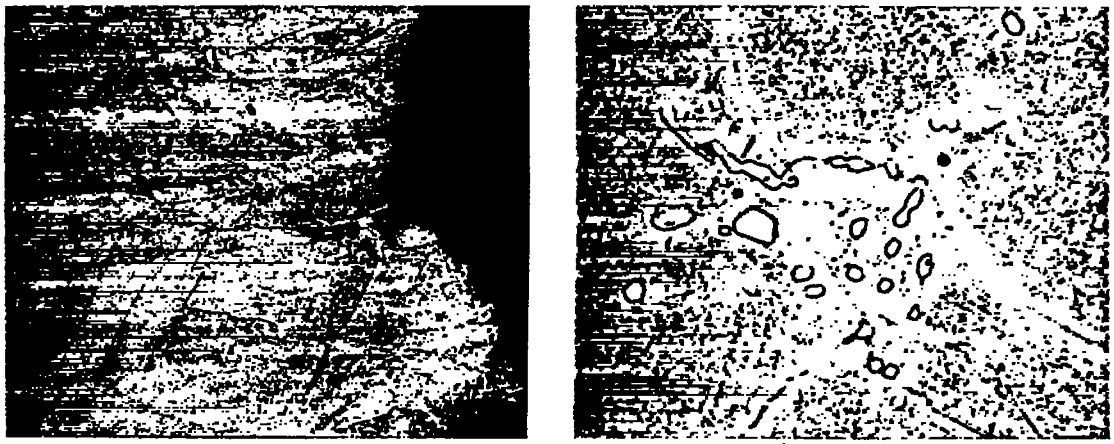


100X 1000X

Specimen 2A1 - 2775 hours at 1500° F and 7000 psi.

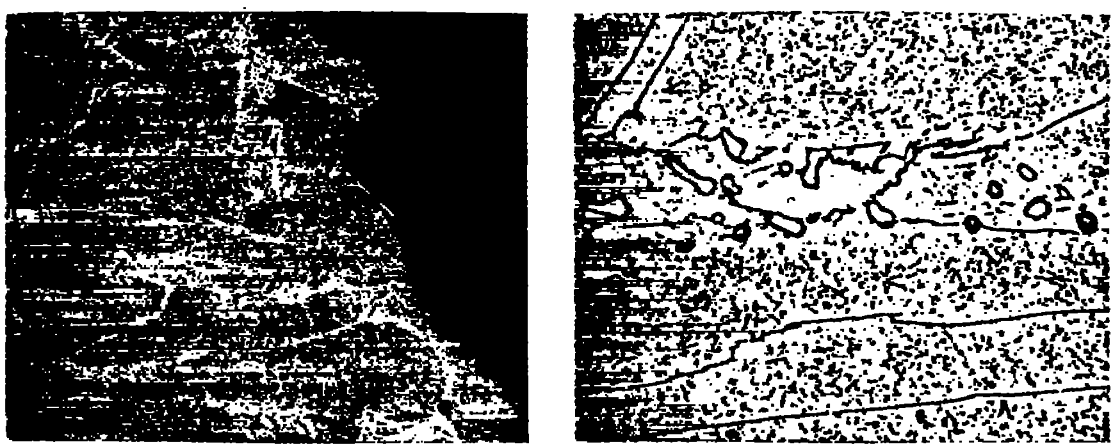
Electrolytic chromic acid etch

FIGURE 29.- MICROSTRUCTURE OF SPECIMENS FROM LOW-CARBON N-155 ALLOY DISC, NR-66E-2L, AFTER CREEP TESTS. WATER QUENCHED FROM 2200° F AND AGED 24 HOURS AT 1500° F.



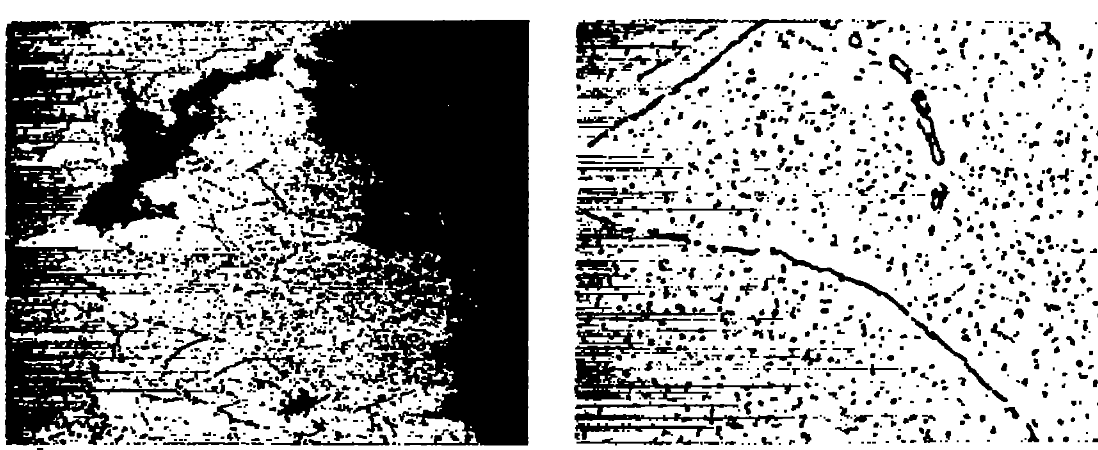
100X 1000X

Specimen 2D4 - 1058 hours for rupture at 1200° F and 35,000 psi.



100X 1000X

Specimen 2C4-2 - 729 hours for rupture at 1350° F and 21,500 psi.

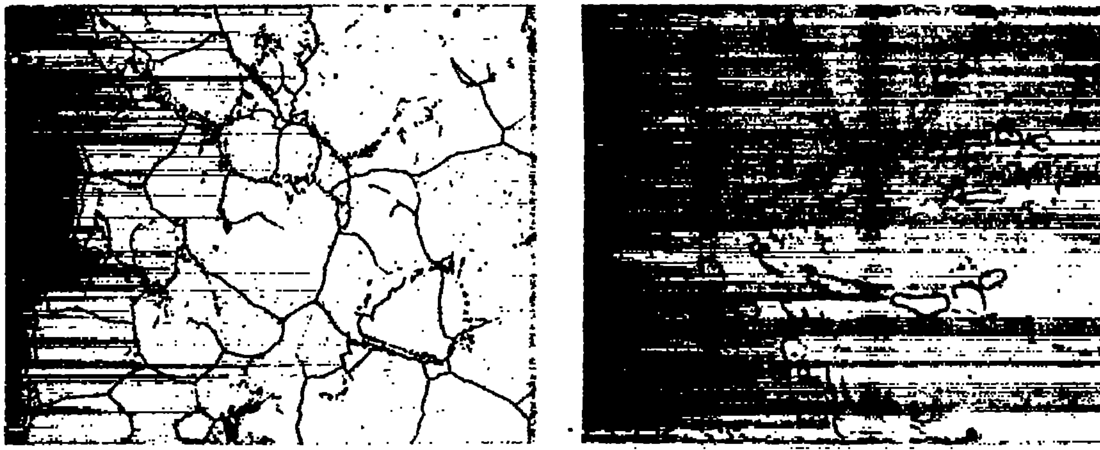


100X 1000X

Specimen 2E4 - 579 hours for rupture at 1500° F and 13,000 psi.

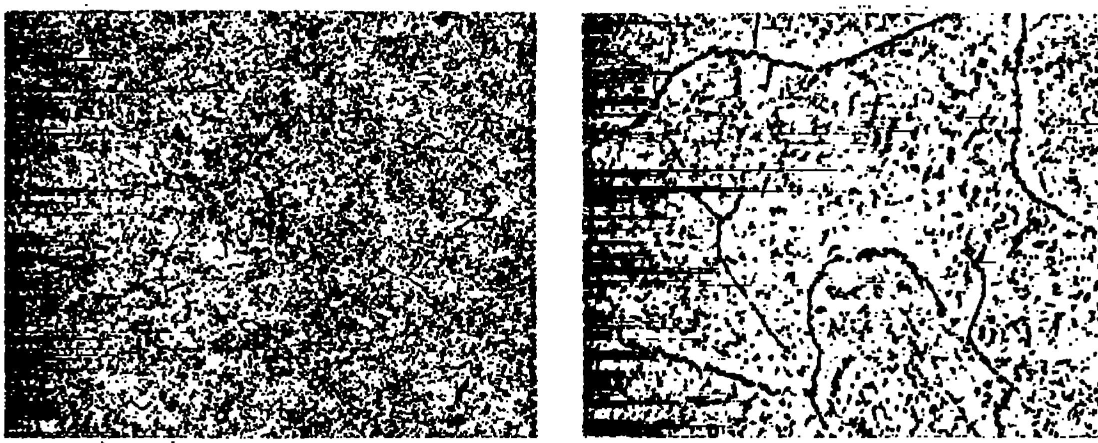
Electrolytic chromic acid etch.

FIGURE 30.- MICROSTRUCTURE OF SPECIMENS FROM LOW-CARBON N-155 ALLOY DISC, NR-66E-2L, AFTER STRESS-RUPTURE TESTS. WATER QUENCHED FROM 2200° F AND AGED 24 HOURS AT 1500° F.



100X 1000X

Specimen 2I3 - 960 hours at 1200° F and 30,000 psi.



100X 1000X

Specimen 2J4 - 2015 hours at 1350° F and 12,000 psi.

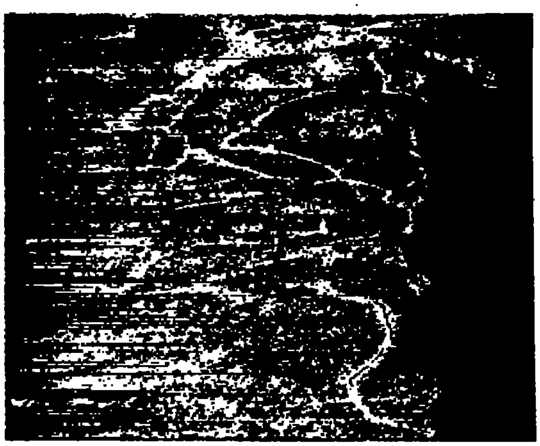
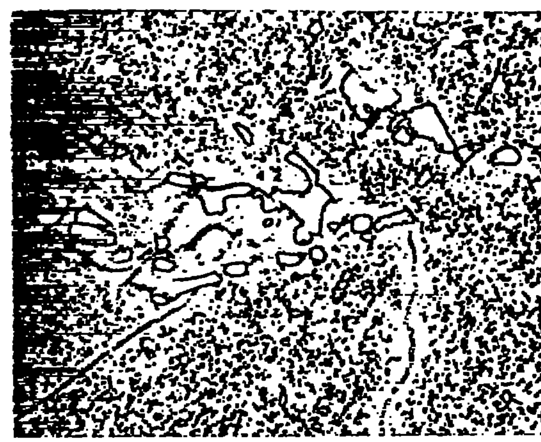
100X 1000X

Specimen 2I1 - 2204 hours at 1500° F and 7000 psi.

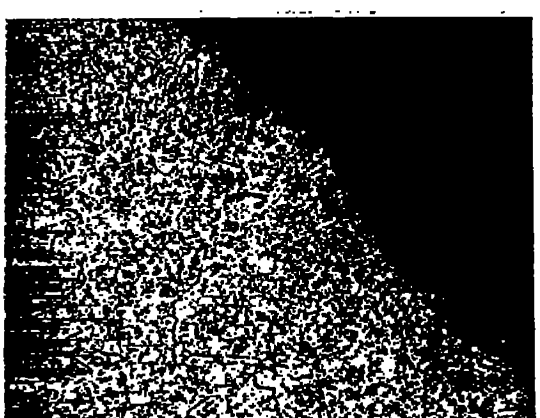
Electrolytic chromic acid etch

FIGURE 31.- MICROSTRUCTURE OF SPECIMENS FROM LOW-CARBON N-155 ALLOY DISC, NR-66E-2R, AFTER CREEP TESTS. WATER QUENCHED FROM 2200° F AND AGED 24 HOURS AT 1350° F.


100X 1000X
Specimen 2K5 - 1536 hours for rupture at 1200° F and 35,000 psi.

100X 1000X
Specimen 2L4-2 - 1068 hours for rupture at 1350° F and 23,000 psi.




100X 1000X
Specimen 2N1 - 485 hours for rupture at 1500° F and 15,000 psi.

Electrolytic chromic acid etch

FIGURE 32.- MICROSTRUCTURE OF SPECIMENS OF LOW-CARBON N-155 ALLOY DISC, NR-66E-2R, AFTER STRESS-RUPTURE TESTS. WATER QUENCHED FROM 2200° F AND AGED 24 HOURS AT 1350° F.